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A METHOD OF FORECASTING OCCURRENCE OF WINTER PRECIPITATION TWO DAYS IN ADVANCE

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ABSTRACT

The application of systematic considerations of upper air conditions to the forecasting of precipitation two days in advance for the Washington-Baltimore area in winter is discussed. Forecasts are made by objective treatment of specific meteorological variables from the 850-mb. and 700-mb. levels. The accuracy of this system is discussed and compared with forecasts made by the usual subjective methods. Comparisons show a strong bias in favor of the methods presented. Use of this system during January 1951 is explained in detail and results indicate significant forecast improvement is possible if an endeavor is made to systematically use present knowledge of certain relationships of conditions aloft to future weather.

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INTRODUCTION

One of the immediate objectives of this research is to improve the weather forecast for a period beyond which extrapolation and similar methods offer very limited assistance. One such problem is to forecast "rain" or "no rain" for "day-after-tomorrow." That this is a logical problem to be considered by forecasters is seen when one realizes that Weather Bureau regulations require the formal issuance of a forecast by 2200 EST each day for the daylight hours (0700–1900) 2 days hence. These advices are of particular value to many important specialized activities if they can be obtained by early afternoon, and if, above all, they are accurate. Now it is the usual practice in the Weather Bureau to issue the public forecast for "day-after-tomorrow" immediately following the analysis of the surface weather map for 1930 EST, but even then the latest map of the upper air which is available to the forecaster is that analyzed from observations made at 1000 EST or 9½ hours earlier. This research, using essentially upper air information, therefore involves a time lag considerably longer than the 48 hours beyond which conventional short-range forecasting techniques are usually considered no longer to apply.

Little or nothing is found in the literature of meteorology and weather forecasting which applies to this problem specifically.[1] This does not deny that subjective methods can be found for preparing prognostic pressure patterns for surface and upper air which can be extrapolated to cover the time lag in question. However, it is well known that such prognoses are often considerably in error for periods of 24 to 30 hours in advance, and even assuming that they could be prepared with a high degree of accuracy, the job of estimating the weather which will accompany these patterns still remains a difficult problem.

Granting therefore that this problem involves much more than the mere extrapolation of pressure centers or precipitation areas, one is led to attempt a systematic interpretation of the field of motion of the upper air within defined frontiers in terms of potential availability of moisture, speed of flow, vertical motion, blocking, deepening, filling, and possibly many other factors that one might consider in preparing a forecast for "day-after-tomorrow." How then are we to evaluate these many items in a systematic fashion, giving each its proper weight in the solution of this daily problem?

[1] A notable exception is a paper by Vernon [1] describing a method for forecasting precipitation 24–48 hours in advance at San Francisco.

This study was started in December 1949 in an attempt to answer this question and thus to make available to the forecasters a system which could be checked each day in an effort to improve the forecasts in question during the winter months (December, January, February). A provisional system, which was an attempt to incorporate the ideas as described in the following section of this report, was developed and tested within a few weeks time.

DEVELOPMENT OF THE PRELIMINARY FORECAST AID

During the winter months, a forecaster preparing forecasts for areas along the east coast of the United States is apt to consider first of all whether or not flow channels at intermediate and/or higher levels of the atmosphere are or will be present through which moisture will arrive from the Gulf of Mexico during his forecast period. (See [2] for example.) Thus, precipitation would be unlikely in a situation in which this condition was lacking, though its presence would in no way guarantee precipitation at a particular spot during the period in question. Nevertheless the study proceeded with the following attempt at defining the presence or absence of this condition.

The variable first considered as an index of the type of flow necessary for receiving moisture from the Gulf was the position of the High cell aloft which is usually present somewhere over or near the southeastern United States during winter months. As an index of time of occurrence of precipitation, pressure falls in the western half of the country were considered.

It was soon found that the 700-mb. chart did not provide useful indices of these variables as the southeastern High frequently did not extend to that level and troughs often developed too late at that level to be used in forecasting for more than 24–36 hours in advance. However, the 850-mb. chart seemed to give much better indications of "opening the Gulf" (a flow northward from the Gulf) and position of the southeastern High. Correlations of position of the southeastern High at 850 mb. with location of centers of largest 24-hour height falls at 850 mb. (west of the Mississippi) gave indications of being very useful. If the southeastern High was located far enough east so that Miami had an easterly or southerly flow at 850 mb. and height falls were located in certain areas in the Southwest and Middle West it was found that precipitation frequently occurred in Washington and/or Baltimore 2 days hence. If the High was pushed so far south that a westerly flow was prevailing at 850 mb. in the Gulf, or if the High was bridged from Florida through Texas, then rain was unlikely. Although this method gave promise of usefulness, it lacked strict objectivity since two different persons would not always indicate the southeastern High, frequently of peculiar size and shape, to be in the same specified area. Therefore, it was decided to determine, if possible, a strictly objective parameter that could be used in place of the "position of southeastern High."

Since we usually look for the Gulf to "open" before precipitation can develop, and since our forecast period was to begin quite some time in the future, it was decided to use the upwind flow from some station to the southwest of Washington (and yet not too far west) to give an indication of flow from the Gulf area. Nashville was the station selected for this check as it is the only upper air station between Washington and the Mississippi River, to the west or southwest of Washington. Since, in daily forecasting procedures, it was recalled that rain frequently had developed after the 850-mb. contour through Nashville could be traced upwind into the Gulf, except when there was a definite anticylonic curvature to this flow, it was decided first to evaluate this one parameter for forecasting "rain" or "no rain" 2 days in advance for Washington and Baltimore. The rule for using the parameter was stated as follows:

> If the 850-mb. contour through Nashville, traced upwind, crosses the 25th parallel (north latitude) east of longitude 100° W. and this intersection is not east of another upwind point on the contour between Nashville and the intersection, forecast "rain." Forecast "no rain" for all other types of flow not thus defined.

Figure 1 illustrates examples of the types of flow which will result in either a "rain" or "no rain" forecast in accordance with the above rule.

The power of this one parameter derives from its ability to integrate many factors involving timing, moisture, flow, etc. It was felt that if Nashville upwind flow crossed latitude 25° N. to the east of the longitude of Nashville (86° 41′ W.) or if the upwind flow curved back to the east after being farther to the west (fig. 1 B), that the High in the Southeast was too strong to permit a trough to move through or to permit sufficient moisture to reach the Washington area by the forecast period. If the upwind flow was from the southwest but then curved back to the northwest without crossing as far south as latitude 25° N. (fig. 1 C), then in many of these cases the trough which might otherwise help bring in the precipitation would be too far east or moving eastward too fast for rain still to be occurring 2 days hence at Washington or Baltimore. When the flow is from the northwest aloft (fig. 1 C) it is usually too dry for precipitation or else there is insufficient time for a new trough to develop and move eastward far enough to cause precipitation on the east coast. As there are other factors with which a parameter of this kind is correlated (vertical motion, overrunning, cyclone movement, etc., c. f. Fleagle [3]), it was thought that by first determining the value of this parameter alone it would be possible then to add other factors including pressure changes to improve the one-parameter forecast.

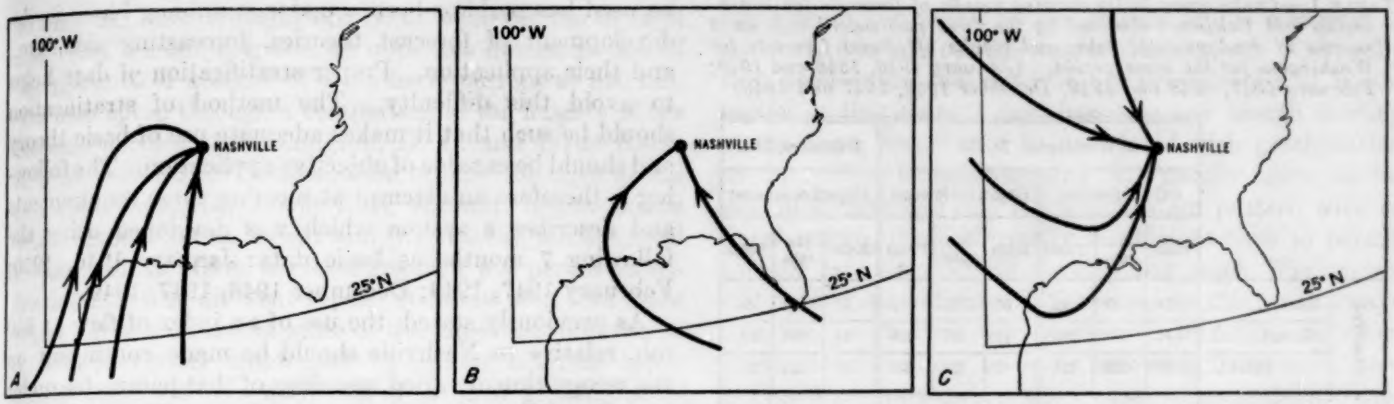

FIGURE 1.—Examples of types of 850-mb. contours through Nashville which result in either a "rain" or a "no rain" forecast for Washington, D. C., 2 days hence according to the "single-parameter" rule. (A) "Rain" forecast, (B) "No rain" forecast, (C) "No rain" forecast.

Results on dependent data [2] for 9 different winter months through a 4-year period, 1946 through 1949, are summarized in figure 2 and table 1. The percent and skill scores shown are for application of the system to Washington and Baltimore considering 0.01 inch or more of precipitation to verify a "rain" forecast and a "trace" or zero precipitation to verify a "no rain" forecast. The results for Washington are also compared with the official forecasts made for exactly the same period.

The results for Washington, using only one parameter, gave a score of 85.6 percent correct and a skill score [3] of 0.56 as compared with 67.5 percent and skill score of 0.20 for the official forecasts. Although good scores are to be expected on dependent data, the superiority over official forecasts was far beyond what was expected; the original goal was to try to develop a system which would perhaps give a score of 75 to 80 percent for forecasts 2 days in advance. It should also be pointed out that the scores made on the official forecasts had the benefit of surface data available approximately 9 hours after the upper air soundings used by the one parameter system.

It was realized that in the nontypical cases when extremely warm weather occurs in the East during winter months, due to a warm High building up in the Southeast, the one parameter rule would frequently break down by indicating precipitation when none would occur. This was the case in January 1950, a month during which the official scores were also much below par. It was therefore decided that this study would have to be expanded in some manner to take care of these cases in which rain does not move to the east coast even though the flow aloft is from the Gulf of Mexico. Also, if such a system is to be of maximum practical value it should attempt to forecast rains that occur at times after the existence of a northwesterly flow aloft. As shown by the contingency table (table 1) the one parameter system forecast precipitation only 47 times whereas precipitation actually occurred 62 times at Washington. An ideal system should indicate precipitation at least as many times as preciptitation occurs, that is, the basic material should be developed to do this.

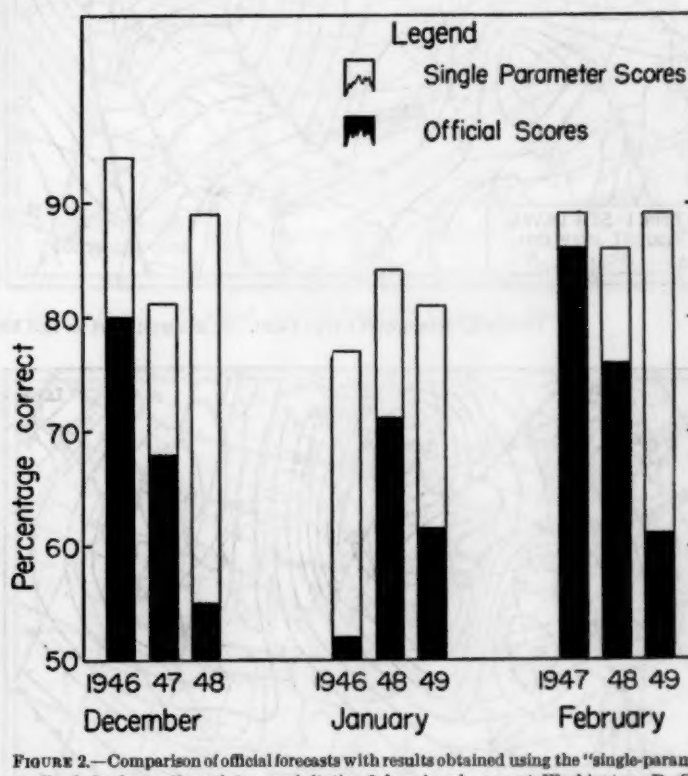

FIGURE 2.—Comparison of official forecasts with results obtained using the "single-parameter" rule for forecasting winter precipitation 2 days in advance at Washington, D. C.

[2] The results for the 9 months discussed above are considered to be derived from basic or dependent data since these same months were used when trying to develop the original two-parameter study. However, some additional months were tested with about the same results and December 1949 was outstanding with a score of 94 percent correct.

[3] The formula for computing the skill score is:

$$S=\frac{C-E}{T-E}$$

where C=number of correct forecasts, T=total number of forecasts, E=number of forecasts expected correct due to chance.

TABLE 1.—*Contingency tables showing results of forecasts for Washington and Baltimore obtained by the "one parameter" rule on 9 months of developmental data, and results of official forecasts for Washington for the same period. (January 1946, 1948 and 1949; February 1947, 1948 and 1949; December 1946, 1947 and 1948)*

		Washington, D. C.						Baltimore, Md.		
		Official forecast			Objective forecast			Objective forecast		
		Rain	No rain	Total	Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	31	31	62	35	27	62	33	30	63
	No rain	57	152	209	12	197	209	14	194	208
	Total	88	183	271	47	224	271	47	224	271
		Percent correct = .67 Skill score = .20			Percent correct = .86 Skill score = .56			Percent correct = .83 Skill score = .50		

DEVELOPMENT OF THE MORE COMPREHENSIVE SYSTEM

METHOD OF STRATIFICATION

The lack of a logical determination of the conditions under which a given forecasting system or variable shall be used has perhaps been a major stumbling block in the development of forecast theories, forecasting aids, etc., and their application. Proper stratification of data helps to avoid this difficulty. The method of stratification should be such that it makes adequate use of basic theory and should be capable of objective application. The following is therefore an attempt at meeting these requirements and describes a system which was developed using the following 7 months as basic data: January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949.

As previously stated, the use of an index of flow at 850 mb. relative to Nashville should be made contingent on the recognition of varied meanings of that parameter under broadly different synoptic situations. Thus with the presence over the eastern United States of a warm High, wherein the southwesterly flow at 850 mb. over Nashville was perhaps a vertical extension of similar flow near the ground, no overrunning would be present which could accelerate the vertical motion. This situation might be reversed should a cold High be centered over the northeastern United States. Therefore in the search for a broad index of the synoptic situation, sea level pressures at

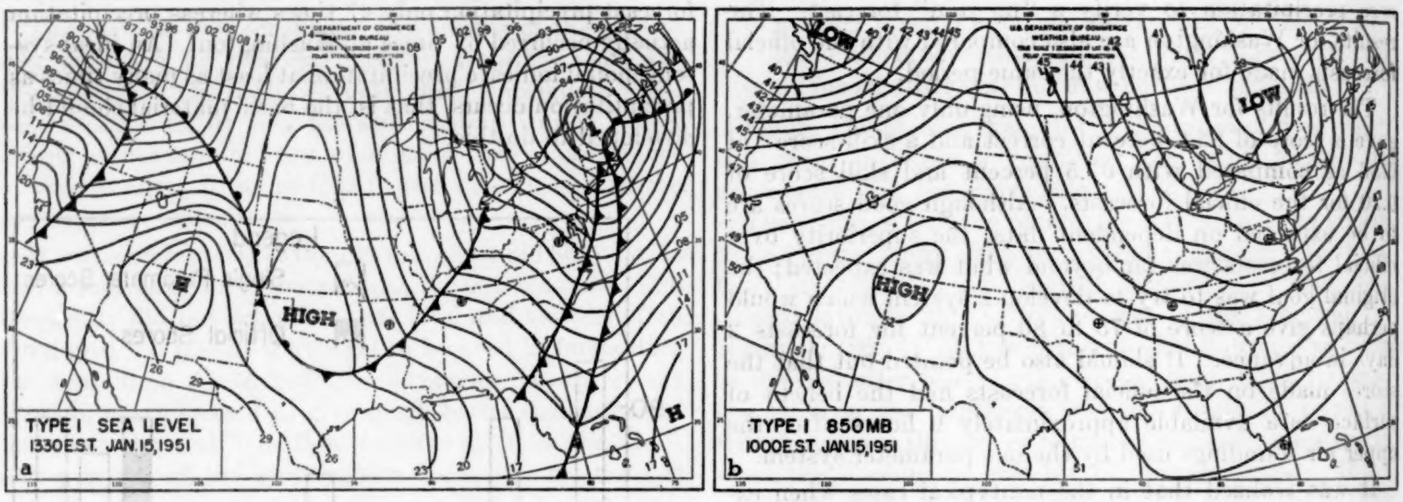

FIGURE 3.—Example of a type 1 case. (a) Sea level chart for 1330 EST, January 15, 1951. (b) 850-mb. chart for 1000 EST, January 15, 1951.

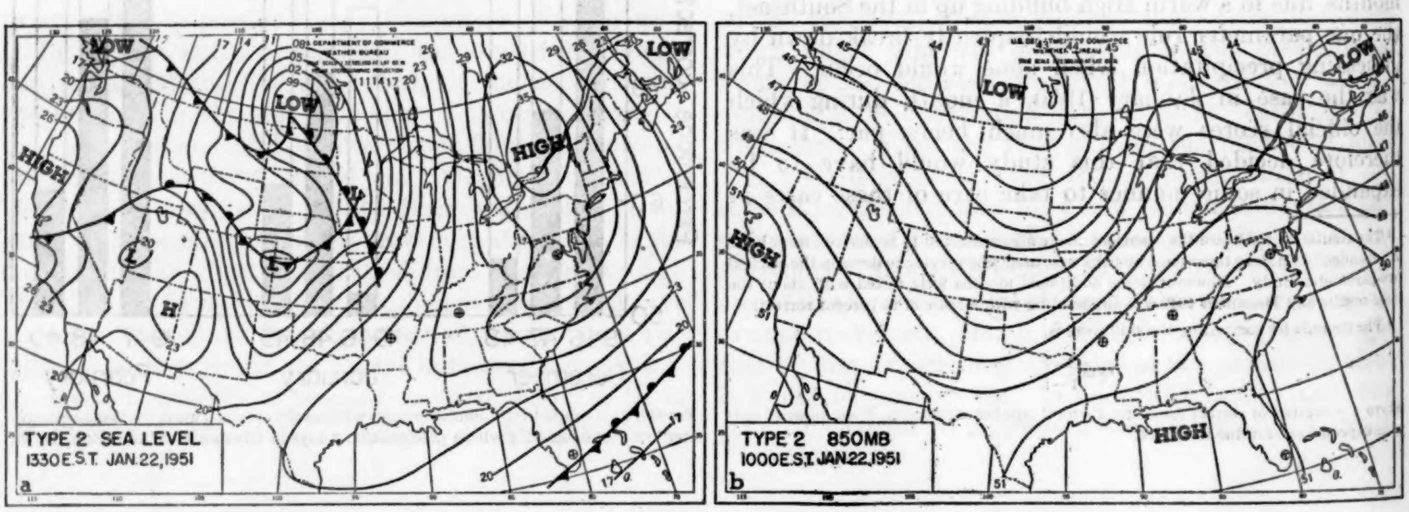

FIGURE 4.—Example of a type 2 case. (a) Sea level chart for 1330 EST, January 22, 1951. (b) 850-mb. chart for 1000 EST, January 22, 1951.

Miami, Fla. and Washington, D. C. were compared as of 1330 EST. Following this an objective determination of the presence or absence of a southerly current at 850 mb. was attempted through a comparison of the heights of the 850-mb. surface at Washington, D. C. and Little Rock, Ark. at 1000 EST. Consideration of only the signs of the two differences, (a) Little Rock 850-mb. height minus Washington 850-mb. height and (b) Washington sea level pressure minus Miami sea level pressure, will permit stratification into four different types. It can be seen that these types will in part reflect some of the important differences in flow previously mentioned. The four different types thus isolated will now be reviewed for their general meteorological implications in terms of weather 2 days hence, and more particularly, the nature of the weather situations falling into each of the four categories will be briefly discussed. Reference should be made to figures 3 through 6 for examples of actual situations illustrating the four types.

Type 1 includes all cases where the 850-mb. height at Little Rock is greater than that at Washington and the sea level pressure at Washington is lower than that at Miami. Such a combination implies in most cases low pressure to the north at the surface and a westerly or northerly flow aloft to the west of Washington. Generally such a condition does not result in precipitation at Washington or Baltimore 2 days hence as any trough existing at the time, which may be associated with precipitation on the current or following day, will usually move too far east in 2 days carrying its precipitation pattern with it. Furthermore, there is usually insufficient time to permit another rain situation to develop and reach Washington within the time indicated. Nevertheless, this is not always true and parameters were developed to determine when precipitation is likely to occur following these situations.

Type 2 groups together those cases wherein the 850-mb. height at Little Rock is less than that at Washington and the sea level pressure at Washington is greater than that at Miami. Days on which the flow patterns fall into this classification are frequently followed by precipitation at Washington 2 days hence. Here we have the ideal overrunning type, with easterly or northerly flow indicated at the surface and southerly flow aloft. However, the problem of timing is a major element to be considered in deciding whether the precipitation which is to occur

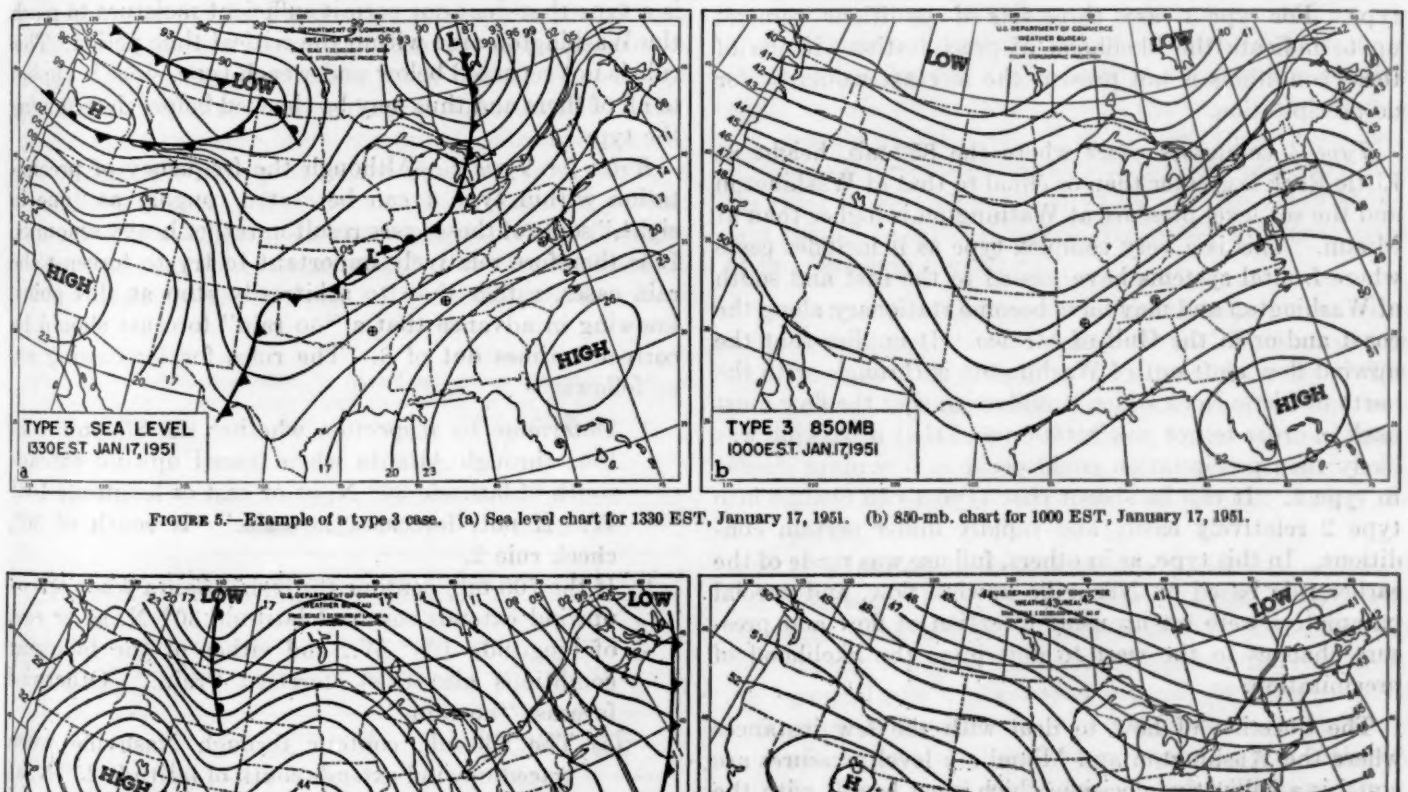

FIGURE 5.—Example of a type 3 case. (a) Sea level chart for 1330 EST, January 17, 1951. (b) 850-mb. chart for 1000 EST, January 17, 1951.

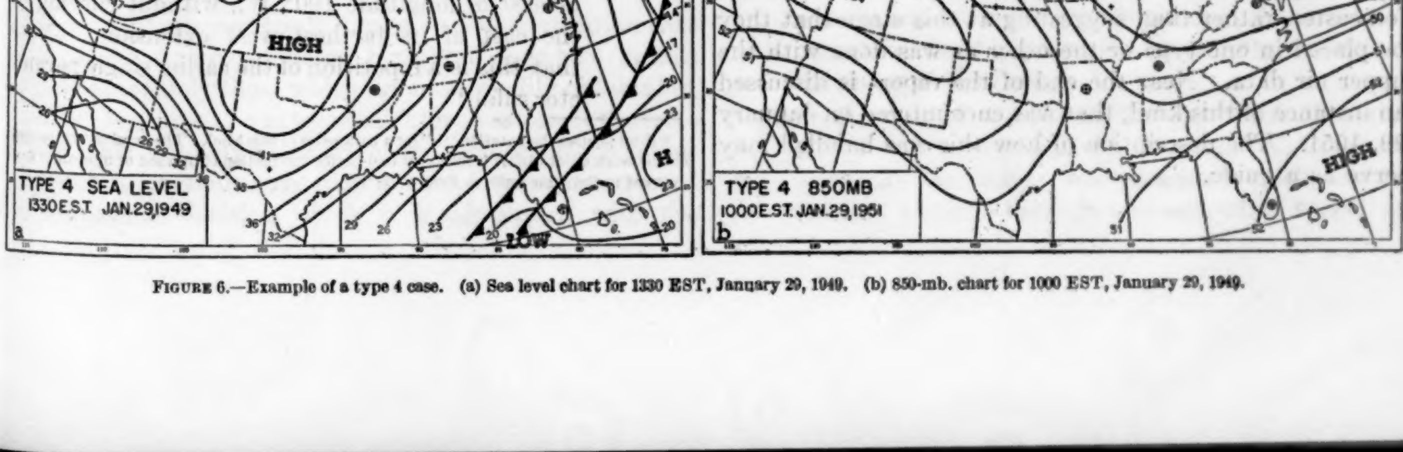

FIGURE 6.—Example of a type 4 case. (a) Sea level chart for 1330 EST, January 29, 1949. (b) 850-mb. chart for 1000 EST, January 29, 1949.

will fall during the daylight hours of "day-after-tomorrow." In some instances the rain will occur but will have ended by the beginning of the 12-hour forecast period. Likewise, the movement of the trough or other rain producing mechanism may be so slow that the precipitation will not reach Washington until after the end of the 12-hour period. Therefore, in dealing with this type, it was first assumed that precipitation would occur, then rules were formulated to cancel this preliminary rain forecast if one of several specific conditions existed. This procedure is similar to that outlined in another study by the author [4]. Type 2 is the only type in this paper to which this line of reasoning is applied. In the other three types parameters are introduced which are aimed at indicating if and when precipitation is likely to occur; if a positive indication is lacking the forecast is then for "no rain."

Type 3 groups those cases where the 850-mb. height at Little Rock is the same or less than at Washington, and sea level pressure at Washington is less than at Miami. This type then includes the "warm High" cases since it automatically includes cases with southerly flow at surface and aloft. Of course it also includes cases with southerly flow when the high pressure cell was not of the "warm" type. For type 3 cases three sets of conditions were set up to indicate the likelihood of precipitation—if one of these conditions is not present the forecast would be for no precipitation.

Type 4 comprises cases where the 850-mb. height at Little Rock is greater than or equal to that at Washington and the sea level pressure at Washington is higher than at Miami. This is a very complex type as it includes cases where frontal systems have passed to the east and south of Washington and may have become stationary along the coast and/or in the Gulf of Mexico. It implies that the upwind flow aloft out of Washington is through or to the north of Little Rock which would mean that the flow must back in order to get precipitation and that if backing was likely then precipitation could occur in a manner similar to type 2. It can be shown that type 4 can change into type 2 relatively easily and rapidly under certain conditions. In this type, as in others, full use was made of the earlier rule based on Nashville upwind flow, and special parameters were set up using direction of flow and pressure changes to the west to determine the likelihood of precipitation.

The question of how to deal with the few instances where the Washington and Miami sea level pressures are equal is a subjective decision which must be left with the forecaster, rather than suggesting at this stage that they be placed in one type or the other as was done with the upper air data. Near the end of the report is discussed an instance of this kind, that was encountered on January 29, 1951. The description of how this was handled may serve as a guide.

OUTLINE OF THE FORECASTING SYSTEM

In actual practice, this system is applied by using a single "work sheet" upon which the forecaster enters the results obtained in following the steps of the forecast procedure. First of all the forecaster makes the necessary comparisons of the 850-mb. heights at Little Rock and Washington and the sea level pressures at Washington and Miami. This immediately indicates which one of the four types is to be considered and the forecaster then refers only to the rules in that portion of the work sheet dealing with that type. (A sample of this form will be found later in the report (fig. 7) in a section which describes the use of the system in actual daily forecasting during January 1951.)

There is, however, one rule which may be used to eliminate a forecast of rain without the necessity of any further checking. This rule, which describes a broad northwesterly flow aloft extending to the southern tip of Florida, is stated as a function of the 700-mb. contour through Miami. If the upwind tracing of this contour from Miami passes north of either Little Rock or Nashville, forecast "no rain." This type of flow is usually present only with a very strong ridge west of Miami and is a type that does not permit sufficient moisture to reach the Washington area within the critical time period. This rule is not repeated below under each type, since it applies to all of them and thus may be checked before determining the type.

Rules for Type 1.—Although the frequency of precipitation within type 1 can be stated roughly as "one in eight," some of these cases result in rather heavy amounts. It is therefore relatively important to try to forecast the rain cases, rather than to arbitrarily stop at this point, knowing in advance that a "no rain" forecast should be correct 7 times out of 8. The rules for forecasting are as follows:

1. Determine by inspection whether the 850-mb. contour through Atlanta when traced upwind extends south of latitude 30° N. at or east of longitude 108° W. If not, forecast "no rain." If south of 30°, check rule 2.
2. If the 700-mb. contour through Atlanta when traced upwind extends south of latitude 30° N. at or east of longitude 108° W., and either of the following conditions also exist, forecast "rain." Otherwise forecast "no rain."
   (a) The 850-mb. contour through Nashville when traced upwind extends south of latitude 25° N. at or east of longitude 100° W., without curving to the east of its farthest west extension. (Note that this is a repetition of the earlier single parameter rule).[4]

[4] Brier [5] uses the notation "L" for a parameter of this kind. The symbol "L" as used in the work sheet (fig. 7) is intended to describe the motion of upwind or upcontour flow but not in the same units as Brier's "L".

(b) If the 24-hour height change at 850 mb. at Nashville is not more than +30 feet, *and* if the 700-mb. height at Ely is greater than that at Grand Junction, forecast "rain," except forecast "no rain" with this condition if the 700-mb. heights at both Grand Junction and Big Springs show 24-hour rises and the 700-mb. height at Nashville shows a 24-hour fall. (This rule implies that 24-hour rises of 40 feet or more at 850 mb. at Nashville indicate too much strengthening of the ridge to permit eastward movement of precipitation to the east coast. The latter portion of the rule indicates that if the trough at 700 mb. is west of Grand Junction it is too far west to help produce rain by the end of the forecast period. On the other hand if the trough is east of Grand Junction with the given kinematic height change distribution, the trough will move eastward too far to permit rain to continue in the Baltimore-Washington area during the period in question.)

Within the basic sample of data there were 65 cases which were classified as type 1. Contingency tables showing the results of applying these rules within the basic sample of type 1 cases and summarizing the official forecasts made for the same situations are given in table 2. From these contingency tables, skill scores or percentage of hits above that obtainable through a chance distribution of the same forecasts were computed, showing that the system exceeded the past record of official forecasts by a considerable degree. The system forecasts were 92 percent correct with a skill score of .58 while the official forecasts were 72 percent correct with a skill score of .05. The skill of the system is tested upon independent data in a later section.

TABLE 2.—*Contingency tables for type 1 situations comparing results of system forecasts on dependent data with results of official forecasts. (January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949)*

	System forecast			Official forecast		
	Rain	No rain	Total	Rain	No rain	Total
Observed: Rain	5	3	8	4	4	8
Observed: No rain	2	55	57	14	43	57
Observed: Total	7	58	65	18	47	65
	Percent correct = 92 Skill score = .58			Percent correct = 72 Skill score = .05		

Before discussing type 2 it may be well to mention that the official forecasts quoted here and elsewhere in this report are merely those which are most readily obtainable, without recourse to a categorical interpretation of the forecasts which actually reach the public. Since 1944 Weather Bureau instructions have required the forecaster to record a categorical decision which is in agreement with the published forecasts as of about 2200 EST each day, or about 12 hours after the observations upon which this forecasting system is based, as to whether he expects measurable rain to occur in the rain gage at Washington National Airport during the 12-hour period ending at 1900 EST 2 days hence. It may be argued that this is not a fair comparison, since the forecaster may have been striving for a high "percentage score" which could perhaps bias his skill score. It will be seen from the contingency tables that the forecaster was actually making a serious attempt to forecast the rain which occurred, and that these records are therefore a fair index of the weather which the forecaster actually expected.

Rules for type 2.—Within this type are cases with a broad easterly flow in lower levels (near the ground) above which is a southwesterly flow aloft over the central or eastern United States. Precipitation usually occurs at or near Washington and Baltimore sometime during the 2 days following these cases. However, at times it will have already ended before the beginning of the forecast period and in other cases will be blocked in its movement toward Washington or move northward.

Therefore the rules which follow are based upon the assumption that rain will occur unless eliminated by one of the conditions outlined below. As stated previously, the approach here is similar to that developed in another study by the writer [4] for use in the same region during the month of October. *Any one* of these rules will eliminate a forecast of "rain" and it is not necessary that the rules be checked in the order listed. As stated above, rain should be forecast unless eliminated by one or more of the following conditions:

1. If the 850-mb. contour through Nashville when traced upwind crosses latitude 30° N. east of the longitude of Nashville, forecast "no rain". The presence of this condition usually implies that high pressure is present over the southeastern United States which will block the movement of any trough, Low, or other precipitation mechanism during the period.
2. If a closed Low at 850 mb. is located north of Oklahoma City, between the 98th and 88th meridians, and has moved northward or northeastward during the past 12 hours, forecast "no rain". In general rule 2 is intended to apply to Lows centered south of the Canadian border whose tracks have had all or part of their history south of the Dakotas. In these cases any precipitation which occurs is usually cut off before the beginning of the forecast period by the dry air which moves into the area in the wake of the Low.
3. If the 850-mb. contour through Nashville when traced upwind dips below latitude 25° N. in accordance with the earlier "one-parameter rule", and the 850-mb. contour through Chicago when traced up-

wind stays north of Oklahoma City, and the 850-mb. height at Albuquerque is greater than that at Omaha, forecast "no rain", unless the 850-mb. contour through Pittsburgh dips below latitude 25° N. at or east of Brownsville. (If the Pittsburgh contour does dip below 25° N., or if the 850-mb. contour through Nashville intersects 25° N. latitude east of another upwind point on the contour between Nashville and 25° N., this rule should not be used to eliminate precipitation from the forecast.) In these cases the Low center is usually far enough north and east that the precipitation moves to the north of Washington or else ends before the beginning of the verification period.

4. If Little Rock and Oklahoma City show 24-hour height rises at 850 and 700 mb. and the 700-mb. flow upwind from Dodge City is to the north of El Paso, forecast "no rain". From kinematic considerations this indicates that any trough or Low present between Oklahoma City and the east coast is likely to move too far eastward or northward to still be bringing moisture into the Washington area two days hence. The portion of this rule dealing with the 700-mb. flow upwind from Dodge City is to cover the possibility of a second Low in the Southwest being sufficiently developed to move eastward far enough to result in precipitation in the East during the verification period.
5. If the 700-mb. temperature at San Antonio is 0° C. or lower, forecast "no rain." The reasoning behind this rule is that if air with such low temperatures reaches as far southeast as San Antonio, and to such a depth, any disturbances present or developing to the east of this will be pushed beyond Washington before the beginning of the forecast period two days hence. Originally this rule was tentatively stated to require also that the temperature at Chicago be 0° C. or below, but it was found that this was not needed because in every case in the basic and test data when San Antonio had a temperature of 0° or lower the temperature at Chicago was also 0° or lower.
6. If Oklahoma City heights show 24-hour rises and Nashville heights show 24-hour falls at 850 and 700 mb. and the Oklahoma City 700-mb. height is not more than 20 feet greater than Albuquerque, forecast "no rain." The first portion of this rule is based on the same kinematic reasoning as rule 4 and the latter portion of the rule is to consider the possibility of a "lagging trough" aloft. If Oklahoma City flow at 700 mb. is well south of Albuquerque rain is likely to develop as the result of eastward movement of a "Southwestern Low."
7. If Nashville upwind flow at 850 mb. is through or east of Great Falls, Mont., at the latitude of Great Falls, forecast "no rain." This implies too much northwesterly flow to permit a new trough to move into the East during the period involved and any trough or precipitation condition in the eastern half of the country would be forced too far eastward to be causing precipitation two days hence.
8. If Nashville upwind flow at 850 mb. is closed, due to circulation around a closed Low or a High, forecast "no rain." In this rule the contour through Nashville must remain north of 31° N. in the case of a closed Low, or north of 28° N. in the case of a closed High in order for "rain" to be eliminated. If a closed Low meeting this condition exists, it is not likely to be in a position to cause rain in the Washington-Baltimore area two days hence. If a closed High circulation is present this usually prevents development or movement of precipitation into the forecast area during the forecast period.
9. If the 850-mb. height at Chicago shows a 24-hour fall, and the fall is greater, in a negative sense, than those occurring at Omaha, North Platte, *and* Dodge City (or if those 3 stations show 24-hour height rises), and if Bismarck 850-mb. height is greater than Minneapolis and if Chicago upwind flow at 700 mb. does not go below latitude 32° N. east of San Diego, forecast "no rain." With these conditions, if rain develops and moves into the East-Central States, it will usually have moved to the northeast and/or east of Washington before the forecast period begins.

Caution should be used in trying to apply this system if the situations described in rules 1 and 5 should happen to occur simultaneously. Since rule 1 applies to cases of blocking and rule 5 to cases whereby disturbances are expected to move beyond the area by the time of the verification period, the conflict is obvious. If such rare cases occur, it would seem advisable to discount the two indications of "no rain" thus given and consider that the system is not applicable.

Table 3 shows that on dependent data the system forecasts were 83 percent correct with a skill score of .62 while official forecasts for the same days were 64 percent correct with a skill score of .24. As was shown in type 1 cases, the difference is sufficiently great to encourage the belief that forecasts can be improved through application of this type of technique.

TABLE 3.—*Contingency tables for type 2 situations comparing results of system forecasts on dependent data with results of official forecasts. (January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949)*

	System forecast			Official forecast		
	Rain	No rain	Total	Rain	No rain	Total
Observed: Rain	13	2	15	10	5	15
Observed: No rain	7	31	38	14	24	38
Observed: Total	20	33	53	24	29	53
	Percent correct = .83			Percent correct = .64		
	Skill score = .62			Skill score = .24		

Rules for type 3.—Many of the situations which come under this classification are characterized by the presence of a "warm High" over the Southeastern States. In these situations precipitation at Washington and Baltimore is often inhibited even though the flow at all levels would seem to assure an adequate supply of moisture. Many times in the past this situation has resulted in an incorrect forecast of rain for a period 2 days hence which was actually warm and sunny. Within the 7 months of basic data analyzed in this study, type 3 occurred 23 times and it is interesting to note that 12 of these occurrences were in January 1950, a month during which many all-time high temperature records for January were broken in the eastern United States. However it was possible to isolate three conditions within type 3 that *are* usually followed by precipitation at Washington and Baltimore 2 days hence.

Rules for identification of these three conditions are listed below. Lacking at least one of the three conditions the forecast should be for "no rain."

1. This rule is intended to cover borderline cases wherein the sea level pressure at Washington is only 1 or 2 mb. less than that at Miami. In these cases forecast "rain" if the temperature at the 850-mb. level at Little Rock is 7° C. or more higher than that at Washington, *and* the 850-mb. contour through Nashville when traced upwind dips below 25° N. latitude by or before reaching 100° W. longitude (note that the earlier restriction on the eastward limit of intersection with 25° N. is not applicable here) *and* the 850-mb. contour through Little Rock when traced upwind does not go north of Albuquerque and Grand Junction. Rules 2 and 3 also apply to these cases.
2. If the 850-mb. contour through Pittsburgh when traced upwind is north of Dodge City, and that at Nashville intersects 25° N. by or before reaching 100° W. longitude (again the restriction on eastward limit is not applied), forecast "rain." This rule describes a convergence of westerly and southerly flow at 850 mb. west of Washington in a manner which Namias [6] might describe as confluence. Actually the mechanism visualized in the development of this rule has nothing to do with confluence, but is rather an attempt to describe a situation wherein the trough west of Nashville can move eastward and produce precipitation at Washington 2 days hence rather than remain blocked.
3. If both the 850-mb. and the 700-mb. upwind contours through Oklahoma City go below latitude 30° N. by or before reaching longitude 110° W., forecast "rain". This rule has been inserted to give proper consideration to disturbances which develop sufficiently far to the southwest so as to increase the chances of precipitation in Washington, as compared with cases where Oklahoma City flow aloft is more westerly. In the latter case, disturbances are farther north and precipitation patterns usually move to the north and west of Washington.

Contingency tables covering the results obtained when applying these rules on the 23 type 3 cases studied in the basic sample and a similar table summarizing the official forecasts for the same cases are shown in table 4.

TABLE 4.—*Contingency tables for type 3 situations comparing results of system forecasts on dependent data with results of official forecasts. (January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949)*

		System forecast			Official forecast		
		Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	9	1	10	6	4	10
	No rain	1	12	13	7	6	13
	Total	10	13	23	13	10	23
		Percent correct = 91 Skill score = .82			Percent correct = 52 Skill score = .08		

Rules for type 4.—From the forecaster's viewpoint, type 4 probably appears to be the most complex of all the types. Conditions often develop so that precipitation occurs either east or south of Washington and Baltimore or occurs at these stations immediately prior to the forecast period. The situation at the time of issuing the forecast often involves a cold or stationary front to the south of Washington and although the flow aloft to the west of Washington shows no general southerly flow, such a flow can develop rapidly through a backing of the winds aloft.

Within the 7 months of basic data this type was most frequent of all, with a total of 70 cases, of which 12 were precipitation cases. The forecaster's problem is to accurately forecast a large majority of these cases without over-forecasting. The following rules have been developed:

1. If the 850-mb. contour through Nashville is closed, due to circulation around a closed Low or a High, forecast "no rain". This is the same as rule 8 under type 2.
2. This rule is stated in three parts, the division being made upon an objective measurement of the 850-mb. flow through Nashville. The contour through Nashville is traced upwind, and the lowest latitude reached by this contour between Nashville and 100° W. longitude is noted. (Note that the restriction placed on the contour in the old "single-parameter rule" does not apply. In other words, accept the reading thus indicated regardless of the presence or absence of a more westerly point on the contour.) However, when Nashville 850-mb. upwind flow is to the north of Chicago and/or Omaha before curving southward to below latitudes 25° or 30° N., the upwind flow is considered to have a minimum latitude above 30° N. and rules for flow above 30° as listed under (C) below are applied.

If the lowest latitude reached is:

A. Less than 25° N: Forecast "rain" if the 850-mb. height at Omaha is higher or not more than 10 feet lower than that at North Platte. Otherwise forecast "no rain." This is essentially the old "single-parameter rule" but the comparison between Omaha and North Platte is used to make certain that the trough involved is not already too far east or north to remain in a position to bring moisture into the East 2 days hence.

B. 25°–30° N. inclusive: Forecast "rain" if 850-mb. height at Omaha is the same or greater than North Platte height and there are 24-hour 850-mb. height falls at all raob stations from Bismarck to Big Springs (including Rapid City, North Platte, and Dodge City). Otherwise forecast "no rain." The reasoning behind this rule is similar to that of A above except falls are introduced as a requirement to open the trough sufficiently far to the south to induce a flow of moisture from the Gulf.

C. North of 30° N.:

(i) Forecast "rain" if:

The 850-mb. upwind contour through New Orleans can be traced south of 25° N. latitude by or before reaching 105° W. longitude,

and

The 700-mb. contour through Little Rock can be traced south of 32° N. latitude by or before reaching 105° W. longitude (or can be traced south of El Paso),

and, either

There are height falls (24-hour negative changes) at 850 mb. from Bismarck to Big Springs (including Rapid City, North Platte, and Dodge City),

or

There are 24-hour negative height changes at 850 mb. at Grand Junction, El Paso, and Albuquerque.

Rule (i) is for the purpose of introducing pressure falls from the west and northwest to cause development of a trough of sufficient magnitude to bring about a northward flow of moisture from the Gulf.

(ii) Forecast "rain" if:

There is an 850-mb. trough between Nashville and Miami,

and

The 700-mb. heights at San Antonio and Dodge City are less than at Charleston, S. C. or the 700-mb. upwind contour through Charleston can be traced upwind south of Albuquerque with Albuquerque 700-mb. height at least 20 feet less than that at Charleston,

and, either

There are 24-hour height falls at 850 mb. at all stations from Great Falls to Dodge City (including Lander, Rapid City, and North Platte),

or

There are 24-hour height falls at 850 mb. from eastern Washington through Montana with a central height fall of 220 feet or more.

Though this rule does not include a strict definition of a "trough," this explanatory paragraph should aid in locating these instances. The usual meteorological criteria for troughs should be noted, such as the presence of northwesterly winds at Nashville as compared with southwesterly at Miami, or the presence of lower 850-mb. heights between Nashville and Miami than are reported at either.

The rule (ii) is to provide a means of determining those cases whereby a front which has passed to the south of Nashville, with a northwesterly flow aloft at Nashville, is likely to move back northward as a warm front, or whereby a secondary Low develops in the Southwest and moves northeastward along the front causing widespread precipitation all the way to the east coast. The upwind flow west of Charleston gives indication of the trough lagging far back aloft and the falls are a necessary requirement to cause further development of the Low or trough.

Within the basic data the system forecasts for type 4 were 91 percent accurate, as compared with the 70 percent obtained by the official forecasters when dealing with the same cases. Contingency tables and skill scores for type 4 are shown in table 5.

TABLE 5.—*Contingency tables for type 4 situations comparing results of system forecasts on dependent data with results of official forecasts. (January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949)*

		System forecast			Official forecast		
		Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	11	1	12	5	7	12
	No rain	5	53	58	14	44	58
	Total	16	54	70	19	51	70
		Percent correct=91 Skill score =.74			Percent correct=70 Skill score =.12		

COMPARATIVE SCORES FOR DEPENDENT DATA

The discussion of the frequency and occurrence of rain within each of the four types has been limited to the verification of forecasts as though prepared for Washington, D. C. only. However, in the design of the system attention was paid to verification at Baltimore, Md., and it will be seen from table 6 that the skill is nearly identical when applied to either city. Table 6, showing contingency tables for the 7 months of basic data when all four types are combined, shows again a considerable advance in skill over that shown in the record of the official forecasts for Washington, D. C.

TABLE 6.—*Contingency tables showing results of system forecasts for Washington and Baltimore on dependent data, and results of official forecasts for Washington for the same period. (January 1946, 1950; February 1947, 1949; December 1946, 1947, 1949*

		Washington, D. C.						Baltimore, Md.		
		Official forecast			System forecast			System forecast		
		Rain	No rain	Total	Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	25	20	45	38	7	45	40	11	51
	No rain	49	117	166	15	151	166	13	147	160
	Total	74	137	211	53	158	211	53	158	211
		Percent correct=67 Skill score =.21			Percent correct=90 Skill score =.71			Percent correct=89 Skill score =.70		

From the tables it is evident that the official forecasters were attempting to forecast the precipitation which occurred, but at Washington, D. C., where measurable precipitation occurred only 45 times, it was forecast 74 times, and of these 74 only 25, or approximately one-third, were correct. These may be compared to the forecasts made by this system which not only indicated forecasts of rain with a frequency closer to that with which it actually occurred (note for example the 53 rain forecasts for Baltimore as compared with 51 occurrences of rain) but which also were correct approximately four times out of five on the dependent data.

RESULTS OF TESTS ON INDEPENDENT DATA

Table 7 summarizes the results obtained when the rules which were developed on the 7 months of basic data were applied to the data for an additional three winter months, January 1949, December 1948, and February 1948. Though it may seem that the 3 months mentioned are independent of the original sample of data upon which the system was derived, there can be reasonable doubt as to their independence since they were included as a part of the single-parameter study and examined in the course of that investigation. The system was nevertheless considered as having been tested before being placed in operation at the Weather Bureau Forecast Center at Washington National Airport on December 1, 1950.

TABLE 7.—*Contingency tables showing results of system forecasts for Washington and Baltimore on test data, and results of official forecasts for Washington for the same period. (February 1948, December 1948, January 1949)*

		Washington, D. C.						Baltimore, Md.		
		Official forecast			System forecast			System forecast		
		Rain	No rain	Total	Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	12	13	25	23	2	25	26	2	28
	No rain	21	45	66	12	54	66	9	54	63
	Total	33	58	91	35	56	91	35	56	91
		Percent correct=62 Skill score =.15			Percent correct=84 Skill score =.66			Percent correct=88 Skill score =.73		

From the author's experience it is believed that the skill scores (table 7) which are as high as those attained on the original data are higher than one should reasonably expect to attain within an average test sample. It was hoped, however, that by developing a system which would give a skill of .6 to .7 on basic data, one could reasonably expect that a skill of .4 to .5 could be attained in actual everyday forecasting with independent data.

Beginning on December 1, 1950, the system was in continuous daily use through February 1951, the computations being made by the forecasters on duty with an occasional consultation with the author. Table 8 shows the results of forecasts computed by the forecaster on duty at the time, that is, the forecasts were made 2 days prior to the event.

The method was also tested on January and February 1951 and on additional months of past years by the Short Range Forecast Development Section of the Weather Bureau, with the results shown in table 9. It will be noted that the scores for January and February 1951 are somewhat lower than those obtained when the forecaster made daily use of the system. Since the system is not completely objective, there are some occasions on which a stratification can be decided either way if the location of a contour line or other feature of the analysis is uncertain. It was found by those testing the method that such uncertainties existed on 20 percent of the days during the 8 months test. On 37 percent of those uncertain days, whether the forecast was rain or no rain depended upon interpretation. This indicates that the system has a feature which is desirable in semi-objective systems, namely that the forecaster when actually using the system, can by appropriate interpretation on occasion thereby accomplish an over-all improvement. In the test of the method for February 1951, 5 occasions were found when a decision was uncertain. If all of these occasions are omitted, the skill score for this month rises from .09 to .22.

For years 1943–45, constant level charts were used in the test, with a conversion to constant pressure being made whenever the forecast might be affected by the

TABLE 8.—*Contingency tables showing results obtained by forecasters using the system daily. (December 1950 through February 1951)*

		December 1950			January 1951			February 1951			Combined		
		System forecast			System forecast			System forecast			System forecast		
		Rain	No rain	Total	Rain	No rain	Total	Rain	No rain	Total	Rain	No rain	Total
Observed	Rain	2	4	6	7	2	9	4	1	5	13	7	20
	No rain	1	24	25	2	20	22	4	19	23	7	63	70
	Total	3	28	31	9	22	31	8	20	28	20	70	90
		Percent correct =84 Skill score =.37			Percent correct =89 Skill score =.69			Percent correct =82 Skill score =.50			Percent correct =84 Skill score =.55		

difference between the two types of chart.

From the results of the tests and daily use of the system, it is believed, therefore, that the skill score of .55 with 84 percent accuracy (table 8) is representative of the results that may be expected in future years provided similar charts and data are available, though scores for individual months can vary considerably around these figures as indicated. One should not expect such high skill scores during the latter half of February as tests have revealed that the system is not suitable for the month of March and at times conditions in February are similar to those in March. This phenomenon may possibly be related to a marked decrease in the zonal index of westerlies which Namias [7] has found to occur each year at about this same time.

TABLE 9.—*Percent correct and skill scores for system forecasts for Washington, D. C., for test months. (Tests by Short Range Forecast Development Section)*

Test month	Percent correct	Skill score
December 1943	84	.38
January 1944	76	.12
February 1944	64	.17
December 1944	74	.27
January 1945	84	.44
February 1945	75	.30
January 1951	84	.58
February 1951	64	.09

APPLICATION OF THE SYSTEM DURING JANUARY 1951

Since it would take many pages to show examples of surface and upper air charts depicting the various parameters or cases covered by each of the four main types, it is felt that a discussion of the application of this system during January 1951 would enable the reader to obtain a rather comprehensive picture as to the practical use of this study. Since many readers of the paper will have available to them United States surface and upper air charts for January 1951, they can easily check specific points discussed.

The work sheet used in daily forecasting during January 1951 is shown in figure 7. This sheet shows the pertinent conditions that were considered each day in arriving at the final forecast as well as the verification for Washington and Baltimore.

The following is a discussion of the use of the system for a number of days during January 1951. Data described are from the 1000 EST upper air charts and the 1330 EST sea level charts on the dates shown.

January 1.—This was a typical type 2 case. None of the nine items listed under this type eliminated precipitation and therefore the forecast was for "rain." Rain did develop in the lower Mississippi Valley and moved northeastward very close to Washington, with a trace of precipitation occurring at Washington during the hour before the beginning of the forecast period. Since measurable amounts did not occur at Washington or Baltimore, this is considered as an error.

January 2.—Again this was a type 2 case and since none of the nine points listed eliminated precipitation, the forecast was for rain. Moderate showers occurred with a cold front passage during the forenoon of the 4th.

January 3.—This was a type 3 case but not of the blocking warm High type. None of the three conditions necessary for precipitation were present and therefore the forecast was for "no rain." Fair weather prevailed during the verification period.

January 4.—This was a type 1 case with a fairly strong westerly flow aloft. Since the 850-mb. contour through Atlanta did not extend south of latitude 30° N. the system immediately indicated "no rain" without further checking. The 6th was a fine day.

January 5.—This was a type 2 case with cold air aloft in the Northeast and warm air in the Southwest and a well defined trough developing at 850 mb. from Minnesota south-southwestward into Oklahoma and Texas. The system indicated precipitation since none of the nine steps eliminated such a forecast. A wave from the Southwest caused substantial amounts of precipitation in the Northeast and East-Central States on January 7 and the forecast verified completely at Washington and Baltimore.

January 6.—This was again a type 2 case which suggested the possibility of precipitation. The third step eliminated precipitation, however, for the reason that the pressure trough associated with the precipitation was expected to move beyond the forecast area with the 850-mb. contour through Chicago extending upwind well to the north of Oklahoma City. This was a case where the earlier "one-parameter rule" would have indicated precipitation since the Nashville 850-mb. contour when traced upwind went south of latitude 25° N. However, the rule based on the Chicago 850-mb. contour indicated the rain would end before 0700 EST, January 8. This proved to be the case and although a trace of precipita-

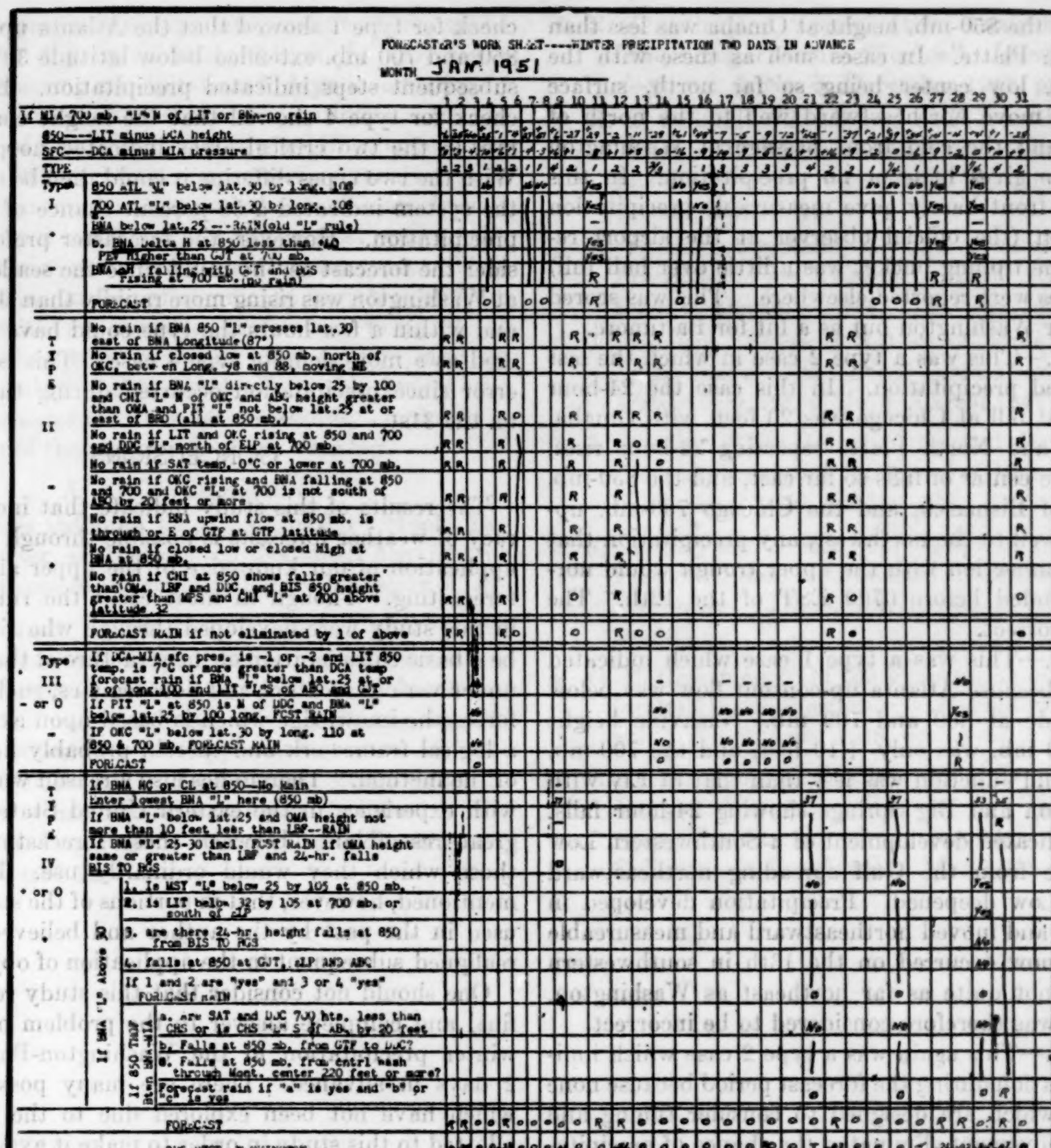

FIGURE 7.—Forecaster's work sheet containing entries made by forecasters during January 1951 in the preparation of forecasts for Washington, D. C.

tion occurred during the 6 hours prior to the verification period, none occurred at Washington or Baltimore during the day period (0700–1900 EST) on January 8.

January 7.—This was a type 1 case and since the 850-mb. contour through Atlanta extended to the northwest no additional checking was necessary and the system indicated no precipitation. Fair weather prevailed on the 9th.

January 8.—This case was a type 1 with the system indicating no precipitation for the same reasoning as on the 7th. There was increasing high cloudiness on the 10th but precipitation did not occur east of the Appalachians.

January 9.—This was obviously a type 4 case with the Nashville upwind contour at 850 mb. reaching as far south as 27° N. In this case there was only one set of conditions to be checked and no precipitation was indi-

cated because the 850-mb. height at Omaha was less than that at North Platte. In cases such as these with the main 850-mb. low center being so far north, surface Lows usually move northeastward well to the north of Washington and the cold front passage at Washington and Baltimore gives little or no precipitation. In this case the cold front barely gave measurable precipitation at Washington (the official observer at the airport reported that the tipping bucket was a little over half full) but only traces were reported elsewhere. This was scored as an error for Washington but as a hit for Baltimore.

January 10.—This was a type 2 case in which the last step eliminated precipitation. In this case the 24-hour 850-mb. height fall at Chicago was 20 feet, with Omaha, Dodge City, and North Platte reporting 24-hour rises. Thus, with the center of falls so far east, and the 850-mb. trough east of Bismarck, and the Chicago 700-mb. up-contour flow well to the northwest, any precipitation that occurred in connection with the upper trough would normally have ended before 0700 EST of the 12th. The forecast was correct.

January 11.—This was a type 1 case which indicated precipitation because Atlanta up-contour flow was below 30° N. latitude at 850 and 700 mb., Nashville height change at 850 mb. was only +10 feet, and the 700-mb. height at Grand Junction was less than that at Ely with Grand Junction and Big Springs showing 24-hour falls. All of this indicated development of a Southwestern Low with moisture from the Gulf spreading northeastward aloft as the Low deepened. Precipitation developed in the Gulf area and moved northeastward and measureable amounts of snow occurred on the 13th in southwestern Virginia but not quite as far northeast as Washington. The forecast was therefore considered to be incorrect.

January 12.—This again was a type 2 case which indicated precipitation during the forecast period because none of the steps which are designed to consider timing and direction of movement eliminated the chance of precipitation. Considerable warm front type precipitation occurred on the 14th in the Washington-Baltimore area and a large section of northeastern United States.

January 14.—This case could have been classified as either type 2 or type 3 since Miami and Washington reported the same sea level pressures. In such instances we have followed the practice in actual forecasting of checking for both types. Type 2 rules indicated no precipitation because the temperature was −4° C. at San Antonio at 700 mb. and therefore any disturbances then present in the East would move too far east or northeast to influence weather in the Washington-Baltimore area 2 days later. Also, none of the conditions that indicate precipitation for type 3 was found. No precipitation occurred on the 16th, and the forecast was verified as correct.

January 29.—As this case could have been classified as either type 1 or type 4 both types were checked. The check for type 1 showed that the Atlanta upwind flow at 850 and 700 mb. extended below latitude 30° N. and the subsequent steps indicated precipitation. However, the check for type 4 showed that the height changes at 850 mb. in the two critical areas indicated no precipitation. With the two types differing it could then be assumed that the system indicated a 50 percent chance of measureable precipitation. However, the forecaster preferred to consider the forecast as "no rain" since the sea level pressure at Washington was rising more rapidly than that at Miami and within a few hours the type could have been considered as a more definite type 4 case. This is listed as an error since precipitation occurred during the entire day on the 31st.

CONCLUSIONS

The results of this study indicate that increased accuracy of weather forecasts is possible through a systematic application of our knowedge of the upper air to weather forecasting. Though in most cases the rules presented in this study were developed through what is believed to be a basic consideration of the structure of the atmosphere under various weather and flow regimes, such a discipline forces the knowledge which is based upon experience into a logical framework and therein probably lies the power of the method. Therein lies also a reason why forecasters with experience in the eastern United States will find a great resemblance between these forecasting rules and those which they would ordinarily use. It should be mentioned, however, that in portions of the study concepts used in the past by the author and believed valid were realigned subsequent to the application of objective tests.

One should not consider that this study represents the final and complete answer to the problem of forecasting winter precipitation in the Washington-Baltimore area 2 days in advance. There are many possible avenues which have not been explored due to the limited time allotted to this study in order to make it available to forecasters for use during the past winter (1950–51). These effects, which would include blocking and the jet stream, could be analyzed using data from the nearby Atlantic Ocean, Canada, and Alaska, such attempts not having been made in connection with this investigation. It is hoped that forecasters and researchers will be able to do so and thereby enable the forecasts to reach a still higher degree of accuracy.

There are now indications that basic progress in the science of meteorology will lead to definite improvement in methods of preparing prognostic pressure patterns (see Charney and Eliassen [8] and Cressman [9]) and that through this there can be an improvement in the accuracy of weather forecasts. Further progress in the improvement of pressure pattern forecasting can also lead to improvement in weather forecasts for periods still farther in advance of those dealt with in either phase of investigation through a combination of the results of both. Thus

if an accurate prognostic upper air pressure chart can be prepared for 1 day in advance, this study provides a means of forecasting precipitation 3 days in advance.

One final conclusion should be mentioned. In the earlier phases of this investigation, when it appeared that it would be difficult to improve upon the results obtainable with a single parameter, it appeared that the conclusions reached by Angell and Chen [10] on the west coast of the United States were also valid along the east coast. They stated ". . . the number of significant variables appears to decrease with an increase in forecast period." It appears now that with successful stratification, and up through the 2-day period involved in this study, the number of variables that can be successfully employed is not a function of the magnitude of the time lag.

ACKNOWLEDGMENT

The author is indebted to Mr. Conrad P. Mook, Research Forecaster at Washington National Airport, for valuable assistance in the preparation of this report.

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THE WEATHER AND CIRCULATION OF MAY 1951

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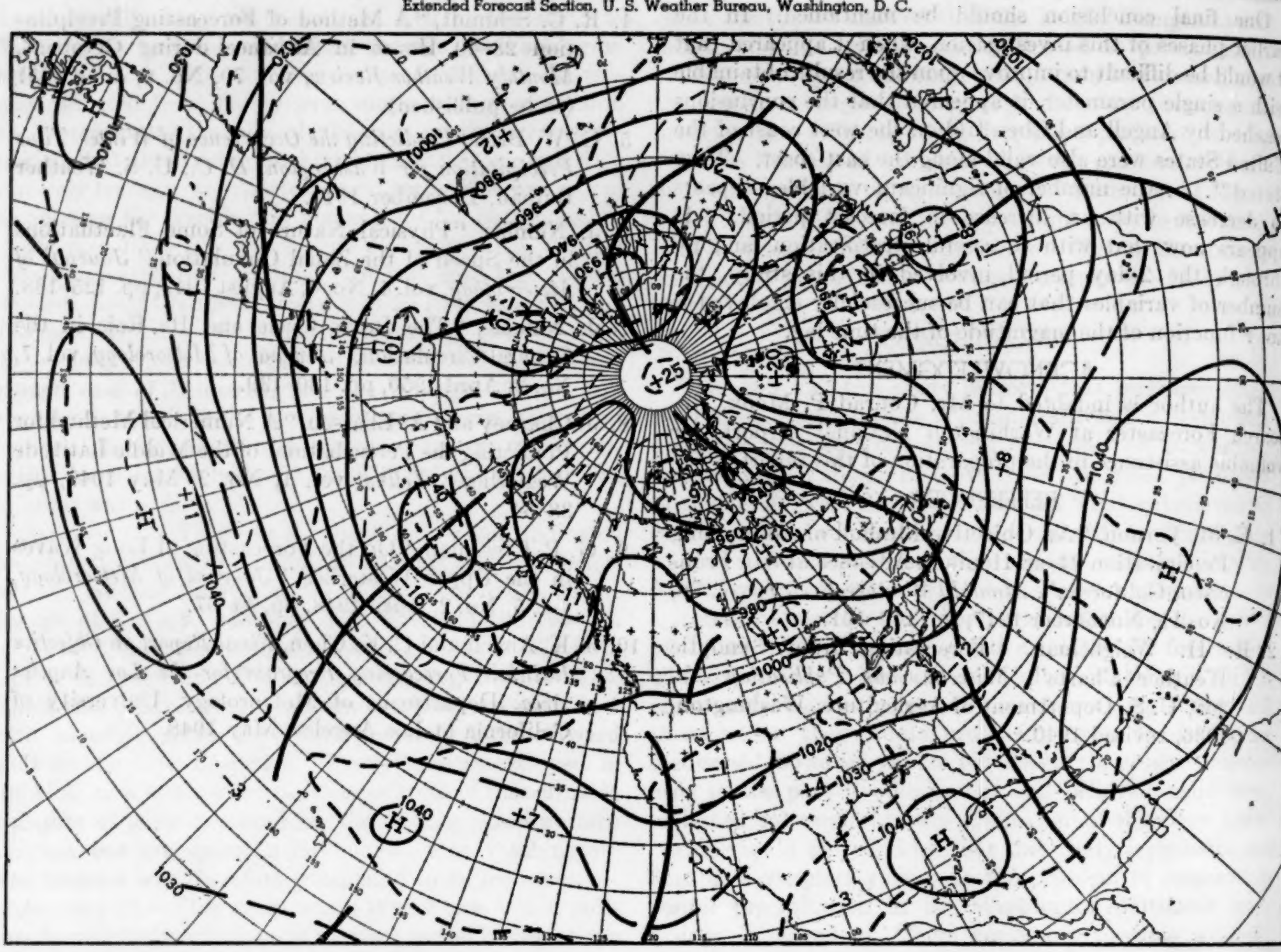

FIGURE 1.—Mean 700-mb. chart for the 30-day period May 1–30, 1951. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departures from normal at 100-ft. intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

THE CIRCULATION

An important feature of the mean circulation over North America and the adjacent oceans in May 1951 was the trough off the east coast of the United States at both sea level and aloft (fig. 1 and Charts XI–XV).[1] 700-mb. heights were below normal in this trough at middle and low latitudes (fig. 1), while sea level pressures were below normal throughout the extent of the trough from the Bahamas to Baffin Bay (Chart XI inset). On the monthly mean 700-mb. chart two distinct centers of negative 700-mb. height anomaly appear in the trough (fig. 1). One center, over the Gulf of St. Lawrence, was the seat of cyclonic activity during the first half of the month, while the other center, off the Carolinas, was prominent during the last 15 days of the month. Likewise, the ridge upstream was characterized by two separate centers of positive 700-mb. height anomaly, one north of Minnesota and the other over Texas. The trough in the southwestern United States was approximately normal in both intensity and position. In the Pacific a deep single-celled Aleutian

[1] See Charts. I–XV following page 105 for analyzed climatological data for the month.

Low was south of the normal position while a strong blocking type ridge dominated Alaska and the Arctic. Blocking was even more pronounced in the eastern Atlantic where a closed warm High was longitudinally superimposed upon a cold cut off Low. As a result below normal heights persisted for the eleventh consecutive month over part of the British Isles [1] [2].

Further information about the mean circulation for May can be obtained from the field of mean 700-mb. geostrophic wind speed (fig. 2). Some of the characteristics of the low index state which prevailed during April [2] and persisted during the first part of May are apparent in the mean wind field. Note the split in the mean monthly jet stream over the United States with one branch going north of the border and the other south of 35° N. Neither of these two jets was particularly strong and between them the monthly wind speeds were quite weak with a minimum speed center located in Nevada. The westerlies also split as they approached the region of blocking in the eastern Atlantic. A center of maximum wind speed was located in the western Atlantic about 700 miles east of the trough off the East Coast. Such an eastward displacement of the wind maximum relative to the trough is generally found in a trough like this one with a pronounced northeast-southwest tilt. The maximum wind speeds (17 m. p. s.) shown in figure 2 were observed in the approximately straight flow between the Aleutian Low and the Pacific High cells. This jet nearly coincides with the zero line on the relative vorticity chart (fig. 3) since in cases of straight flow the relative vorticity pattern is determined by the wind shear.

The effect of the split jet over the North American region on the paths of cyclones is evident in Chart X. Eastward moving cyclones either crossed Canada along the northern jet or traversed the United States north of the southern jet. However, the most intense and frequent storminess occurred in the regions of low pressure at sea level (Chart XI) and well-pronounced cyclonic vorticity aloft (fig. 3) associated with the troughs along the East Coast, in the mid-Pacific and in western North America. There was also a tendency for the cyclones to move along the major axis of the cyclonic vorticity field at 700 mb. In fact, several cyclones seemed to follow the vorticity channels more closely than they did the monthly mean contours.

Perhaps the most pronounced cyclonic activity was associated with the East Coast trough. As the lower latitude portion of this trough intensified after the middle of the month two tropical cyclones developed in the trough. One of these became a hurricane which first travelled southward off the Florida coast and then stalled over the Bahamas before it moved northward toward the Carolina Capes. A hurricane is quite a rarity in May in the subtropical Atlantic and this one was the earliest on record.

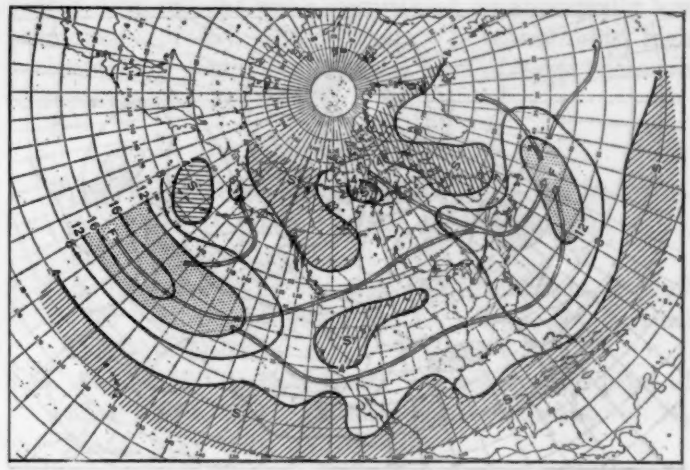

FIGURE 2.—Mean geostrophic (total horizontal) wind speed at 700 mb. for the 30-day period May 1-30, 1951. Solid lines are isotachs at intervals of 4 m./sec. while the double arrowed lines delineate the axes of maximum wind speeds (jets). Areas with speeds in excess of 12 m./sec. are dotted while those less than 4 m./sec. are hatched. Centers of maximum and minimum wind speed are labeled "F" and "S", respectively.

Anticyclones during May (Chart IX) clustered and often intensified in the regions of anticyclonic vorticity at 700 mb. (fig. 3). There were exceptions however to the tendency for the movement of anticyclones to follow the axis of anticyclonic vorticity at 700 mb. Some Highs moved directly across regions of cyclonic vorticity but these were mostly shallow cold anticyclones [3] which generally weakened as they passed through these areas. It is interesting to note that no cyclones took the normal path up the St. Lawrence River Valley. This is not surprising, however, since this region was dominated by abnormally strong anticyclonic vorticity at 700 mb. (figs. 3 and 4).

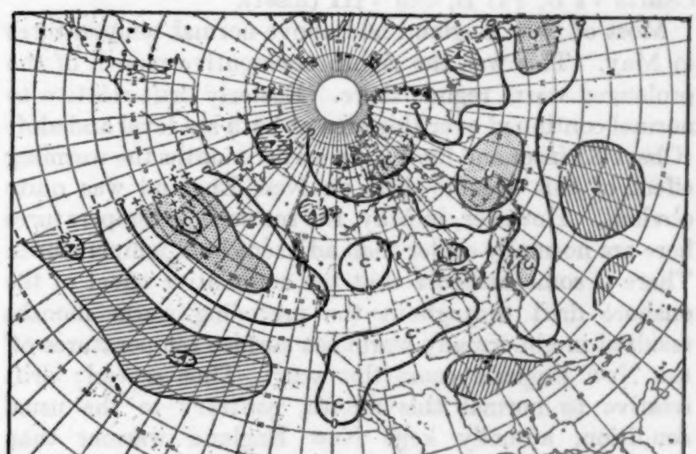

FIGURE 3.—Vertical component of mean relative geostrophic vorticity at 700 mb. for the 30-day period May 1-30, 1951, in units of 10^{-5} sec.$^{-1}$. Areas of cyclonic vorticity in excess of 1×10^{-5} sec.$^{-1}$ are dotted and labeled "C" at the center; areas of anticyclonic vorticity less than -1×10^{-5} sec.$^{-1}$ are hatched and labeled "A" at the center.

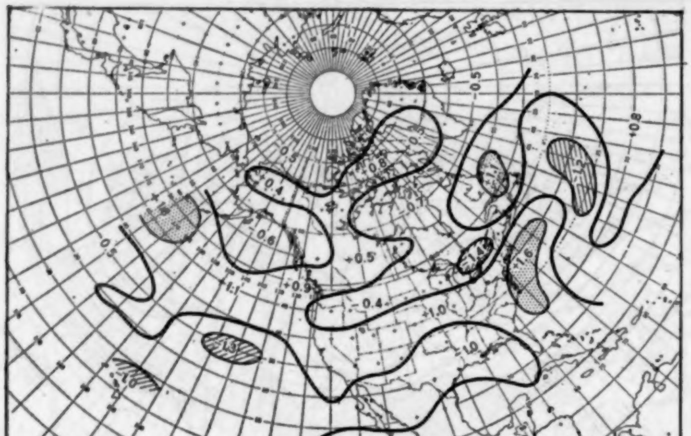

FIGURE 4.—Departure from normal of the vertical component of the mean relative geostrophic vorticity at 700 mb. for the 30-day period May 1–30, 1951. Isopleths of departure from normal drawn at intervals of 1×10^{-5} sec.$^{-1}$ are shown by solid lines with the zero isopleths heavier than the others. Anomaly centers are labeled in units of 10^{-5}sec.$^{-1}$.

THE WEATHER

The pattern of the departure of average temperature from normal (Chart I inset) for May was quite a reversal from that of April [2]. Temperatures were above normal over most of the country with the largest anomaly (about 5° F.) in parts of Wisconsin and Minnesota. The warm weather in the central United States was associated with above-normal heights and anticyclonic curvature at 700 mb. (fig. 1). In the Southwest, the 700-mb. flow relative to normal had a southerly component, while on the West Coast there was weak continental drift relative to normal at sea level (Chart XI inset). The percentage of sky cover (Chart VI A) was reduced in these areas, except the Northwest coast, and thus sunshine (Chart VII A) and solar radiation (Chart VIII) were abundant. The expected departure from normal of these elements is shown in Charts VI B, VII B, and VIII (inset).

Most of New England had above-normal temperatures in May. This was the eighth consecutive month of the prolonged warm regime there. Easterly drift relative to normal continued over this area at both sea level and aloft (Chart XI inset and fig. 1). In earlier months the warming effect of this oceanic drift on New England was quite obvious. However, in May, the sea surface temperatures here are normally cooler than adjacent land temperatures. There is some evidence that the cumulative effect of the onshore drift throughout the preceding warm months resulted in abnormally warm sea surface temperatures off the New England coast this year. Thus easterly drift relative to normal this month, contrary to the usual condition, actually kept New England warmer than normal.

Temperatures were below normal in the Middle and South Atlantic States as northerly flow to the rear of the trough at all levels transported more polar air than usual into this region. The weak trough along the northwest border was accompanied by slightly subnormal temperatures in Washington and Montana. The below-normal temperatures which stretched from North Texas to South Dakota were probably the result of heavy rain (Charts II, III A and III B) and the accompanying cloudiness (Chart VI A) which reduced the sunshine (Chart VII A) and solar radiation (Chart VIII) to well below normal amounts (Charts VI B, VII B, and VIII inset).

Over most of the country May was a rather dry month (Chart III A and B). In fact, in several areas the shortage of rainfall was critical. The rainfall pattern, however, was broken up in typical summer fashion. Several areas of fairly heavy rain were associated with the trough in the Southwest. Parts of Northern California, Nevada, Oregon and Washington received more than normal amounts of rainfall early in the month. To the east of the trough in Arizona and Utah above-normal rainfall continued with amounts totalling more than 200 percent of normal. Unfortunately, very little precipitation reached New Mexico where serious drought conditions were experienced. Only later in the month was this relieved to some extent as shower activity began over the High Plains. The above-normal precipitation in Wyoming and Montana was connected with the weak trough in the Northwest and several storms which moved northward in the Rocky Mountain region (Chart IX).

The region of heaviest rainfall in the United States was centered in the Texas–Oklahoma Panhandles and southern Kansas where amounts exceeding 300 percent of normal were observed. Another region of heavy rainfall extended from North Platte to Chicago. The relatively dry zone between these centers reflects the discontinuous nature of frontal and shower type rainfall. Since only one cyclone passed through this area during the month, most of the rain in the Plains came from heavy showers and thunderstorms associated with several fronts and squall lines. Maritime tropical air, which was transported from the Gulf into the southern Plains at a more rapid rate than normal at sea level (Chart XI inset), supplied the moisture for this heavy rainfall. Some of this convective activity was associated with tornadoes which were more frequent than normal in Kansas and Oklahoma. The heavy rainfall in the Plains States caused many local floods. Serious conditions existed all along the upper Mississippi where levees had been softened by previous weeks of high water.

The small region of heavy rainfall on the mid-Gulf coast of Texas was the result of a cloudburst on the 7th of May in the warm unstable Gulf air preceding a cold frontal passage. At Palacios the 24-hour rainfall amount was 9.26 inches which alone equals nearly 150 percent of the month's normal rainfall. However the rainfall was so concentrated that both the cloudiness and sunshine were about normal for the month (Charts VI B and VII B).

The above-normal precipitation along the East Coast was produced by coastal storms and the hurricane moving up the mean trough. This activity was reflected in the

fields of relative vorticity at 700 mb. (fig. 3) and its departure from normal (fig. 4). Southeastern New England received much of its rain between the 23d and 25th as a slow moving cold front stalled off the coast and a storm center developed on it. By the time this system had finally moved away, it had deposited amounts in excess of 3 inches of rain over the area.

The deep South experienced a serious drought condition that badly retarded the cotton planting. This was associated with stronger than normal ridge conditions at both sea level and 700 mb. (Chart XI and inset and fig. 1). Also related to these conditions was the presence of a center of departure from normal of anticyclonic vorticity over Louisiana (fig. 4). The only relief came late in the month with a few scattered showers. As might be expected, this drought was accompanied by abnormally low percentages of sky cover (Chart VI), abnormally high percentages of possible sunshine (Chart VII) and excessive solar radiation (Chart VIII).

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2. J. S. Winston, "The Weather and Circulation of April 1951", *Monthly Weather Review*, vol. 79, No. 4, April 1951, pp. 71–73.
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THE EAST COAST "BACKDOOR" FRONT OF MAY 16-20, 1951

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INTRODUCTION

The first heat wave that occurs in the late spring over the Mid-Atlantic States is frequently broken by the passage of a "backdoor" cold front. The term, "backdoor front," is used by the meteorologist to identify a cold frontal passage from an easterly or northerly direction rather than from the more normal westerly direction.

The meteorological conditions producing this phenomenon are usually stagnation and intensification of an anticyclone to the northeast of the forecast region. Frequently, the deceleration or stagnation is accompanied by a reorientation of the High cell and a geometric change from perhaps a nearly circular High to one that has a major axis in an east to west direction.

The favorite geographical regions for the occurrence of "backdoor" cold fronts in the United States are the east slopes of the Rocky Mountains and the east slopes of the Appalachian Mountains. In these regions the cold air banks up against the mountains and is forced southward, or southwestward, at a wide angle across the isobars in the area. Thus, the cold air advances farther south than it would ordinarily if the orographic effect were absent.

Along the east coast during the spring months, Polar air that moves southeastward from Canada and out over the cold coastal waters will arrive practically unmodified upon its entrance along the coast of the United States. The associated low temperatures produce marked contrasts in daily temperature readings as this cold air replaces the warm tropical, or the warm return flow connected with a warm ridge or High cell over the Southeastern States.

The vigor of the movement of the surface cold air from the northeast is dependent upon the pattern of the air flow in the mid-troposphere. For the "backdoor front" to advance very far to the south the flow at the 500-mb. level over the area concerned must be from a northerly direction. For the east coast a persistent flow from the northeast at the higher levels is especially favorable.

On May 16, 1951, maximum temperatures rose to near 90° F., from New England southward to Florida. At that time, a cold front was situated along the 45th parallel from Maine to Michigan. The following discussion will describe how a favorable air flow was created. This flow coupled with the air mass in the lower atmosphere pulled the cold air southward into Georgia, and thereby put an end to the incipient heat wave which was advancing upon the Atlantic Coastal States.

PRECEDING SITUATION

Early on May 14, 1951, a sharp, V-shaped, cold trough, at the 500-mb. level, moved eastward over the ocean immediately adjacent to the Atlantic Coastal region. Analysis of the 1500 GMT chart (not shown) for that date revealed that during the previous 12 hours, the sharp wind shear weakened considerably in the zone over Maine to Nova Scotia. As a result, the northern end of the trough continued eastward. In the southern end a large cut-off Low formed with a center 50 to 70 miles east of stationary weather ship "H" (latitude 36° N., longitude 70° W.). As a consequence, the wind pattern associated with the trough was altered. Winds continued from a westerly direction over the northern end of the trough, while to the south they slowly took on the characteristic cyclonic circulation. During the next 2 days the cold cut-off Low developed in intensity, expanded in area and moved southwestward.

At the 700-mb. level on May 15, a large High cell was centered over Kentucky. Most of the eastern United States was covered by this system. As with the upper level, a sharp trough moved eastward off the coast of the United States. This trough developed a cut-off Low about midway between Bermuda and ship "H", 24 hours after the detection of the cut-off Low at the 500-mb. level. During the next 2 days this new Low moved southwestward to within about 100 miles of the Bahama Islands.

Concurrently, the surface weather maps reflected these upper air changes. On May 15, an elongated High cell divided in the vicinity of Maryland; one portion moved out to sea while the other moved to eastern Kentucky and became stationary. Meanwhile, an open wave on the 15th moved from northwestern Ontario to northeastern Quebec. During the next 24 hours this storm moved east into the Atlantic Ocean.

OPENING SITUATION

In the early morning of May 16, a mass of cold air was situated behind the 700-mb. trough over southeastern Canada. The strongest advection of cold air was directed toward the southeast across Quebec. Elsewhere behind the front the cold air advection was weaker with the temperature gradient orientated perpendicular to the stream of northwest winds. The gradient was of the order of 5° C. per 3.5° latitude.

A broad current of air moved eastward, at the 500-mb. level, over southeast Canada with a southern limit over

Massachusetts. The cut-off Low over the ocean caused northeast winds from Long Island Sound southward along the Atlantic Seaboard.

On the surface map for 0630 GMT, May 16 (fig. 1), a cold front associated with the 700-mb. trough extended southwestward from the Low centered over northeastern Quebec. This front curved over southern Quebec and extended westward over Lake Superior to North Dakota. The southwest winds to the south of the storm center were augmented and further extended in area by the return flow of warm air from the large, warm High over the eastern United States.

The warm weather associated with this flow invaded a wide area from the Ohio Valley eastward and northward to include the Mid-Atlantic and the New England States. The onset of this flow caused maximum temperatures, on the 15th, to range from the middle to high eighties from the Gulf Coast to southern Quebec. This warming continued on the 16th, with maximum temperatures for the day of 90° F. at Portland, Maine, 91° at Boston, Mass., 90° at Philadelphia, Pa., and 89° at Washington, D. C. Portland with a reading of 90° at 1330 EST, had a frontal passage shortly before 1930 EST, following which the temperature dropped sharply to a reading of 66° at 1930 EST.

During May 17 the surface cold air mass (fig. 2), moved southeastward across New England and the Canadian Maritime provinces, at a rate slightly greater than twice the southward movement of the Great Lakes portion of the front. This was clearly a reflection of the situation aloft. Where there was strong cold advection the front moved rapidly and where there was weak cold advection the surface front moved more slowly.

The 1500 GMT 700-mb. chart of May 17 (fig. 3) was selected to show the location of the intersection of the cold air boundary with the 700-mb. level. Additionally, the chart illustrates the flow pattern above the surface front. The isotherms continued nearly parallel to the wind flow in the cold air with the exception of the area behind the leading edge of the cold front over the ocean east of Labrador. The temperature gradient, orientation and strength remained unchanged over southeastern Canada. This flow arrangement was not viewed as conducive to any marked southward movement of the cold air. A broad band of weak westerlies dominated the area south of Nova Scotia to southern Virginia. Over the South Atlantic States the winds were easterly in response to the cold Low over the ocean.

The hot weather continued on the 17th south of the cold front with typical readings of 90° at Philadelphia, Pa., 91° at Harrisburg, Pa., and 88° at Washington, D. C. Pronounced cooling followed in the wake of the advancing cold air. Characteristic of the change were Boston, Mass., with a high temperature of 67°, a drop of 24° from the 16th, and Portland, Maine, with a maximum of 62°, a 28° change. The frontal passage at New York City dropped the temperature from an early afternoon high of 80° to a reading of 61° by 1930 EST.

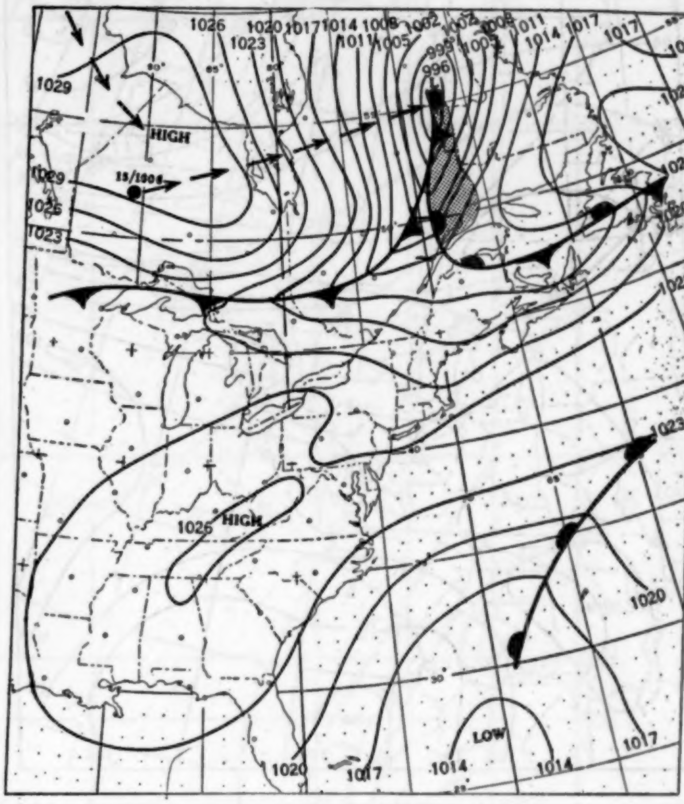

FIGURE 1.—Surface weather chart for 0630 GMT, May 16, 1951. Shading indicates areas of active precipitation. Dots indicate previous 24-hour positions. Numbers to the right of each dot indicate the day and the central pressure (mb.) of the system on that date. Arrows indicate path taken by the center.

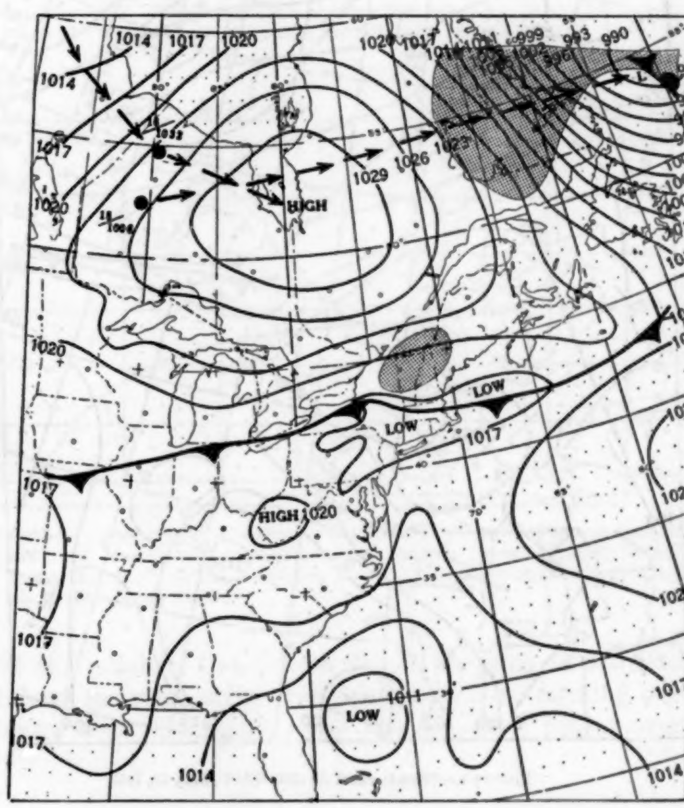

FIGURE 2.—Surface weather chart for 0630 GMT, May 17, 1951.

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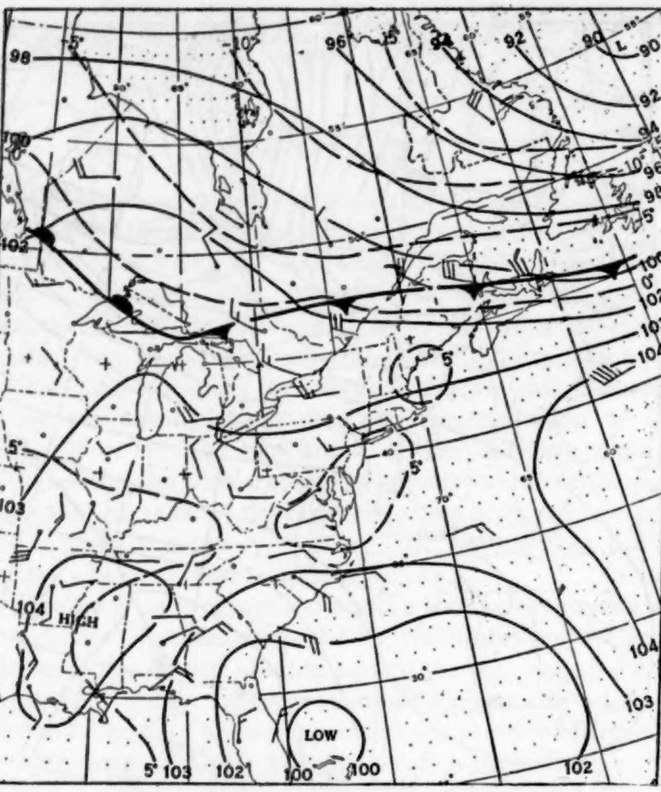


FIGURE 3.—700-mb. chart for 1500 GMT, May 17, 1951. Contours (solid lines) are labeled in hundreds of feet. Isotherms (dashed lines) are drawn for intervals of 5° C. Barbs on wind shaft show wind speed in knots (pennant=50 knots, full barb=10 knots, and half barb=5 knots).

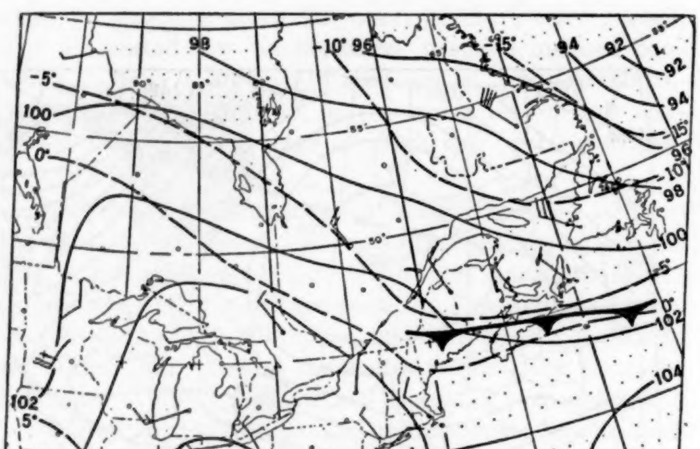


FIGURE 4.—700-mb. chart for 0300 GMT, May 18, 1951.

DEVELOPING SITUATION

During the 12 hours preceding the 0300 GMT chart May 18 (fig. 4), the large elongated cold trough at the 700-mb. level had rotated counterclockwise with the southern end acting as a pivot. This cold Low, in conjunction with the ridge inland and to the west of the Appalachian Mountains, produced northeast winds from Long Island Sound southward along the coast. Of note was the belt of 20- to 40-knot winds from central Virginia southwestward along the coastal plain. This flow of northeast winds above the cold air contributed to the movement of the surface air mass down the coast. Examination of the contours at the 700-mb. level showed no appreciable change during the past 2 days. No cold air advection was evident over the Northeastern States.

On the 18th (fig. 5), the southeastward drifting high pressure center developed into an elongated east-west ridge, with the long axis coinciding with the 45th parallel. The surface trough, induced by the cyclonic circulation aloft, deepened and expanded in extent, with a center identified some 250 miles east of Cape Hatteras, N. C. The surface circulation around this Low acted to retard the ocean portion of the front to the north and northeast of ship "H". However, from north of ship "H" westward to western Pennsylvania, the cyclonic circulation acted to accelerate the southward push of the front. Consequently, the western portion of the front moved south-

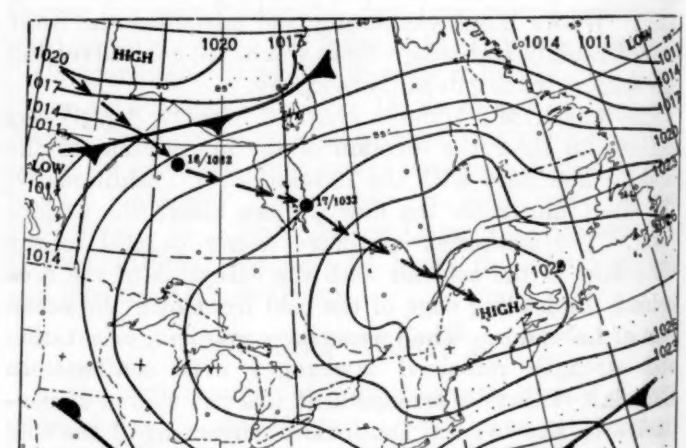


FIGURE 5.—Surface weather chart for 0630 GMT, May 18, 1951.

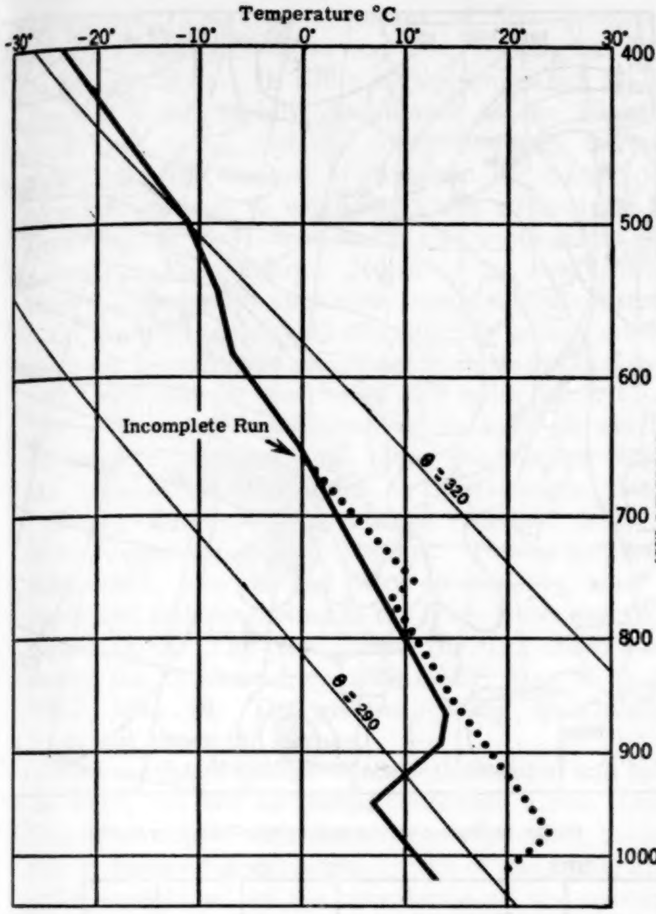


FIGURE 6.—Radiosonde observations (on a pseudo-adiabatic diagram) at Lakehurst, N. J., for 0300 GMT, May 17, 1951 (dotted line), and 0300 GMT, May 18, 1951 (solid line).

ward twice as far as the eastern portion. The greatest 24-hour movement was directed south-southwestward over New Jersey and Maryland. During the day the wind velocity increased from Cape Cod to Maryland indicating added push to the front over Maryland.

The marked lowering of maximum temperatures continued to advance down the coast; Boston had 54°, New York City 67°, Philadelphia 65°, and Washington, D. C. 65°. The Lakehurst, N. J., upper-air soundings at 0300 GMT, May 17 and May 18 (fig. 6), attest to the sharp contrast between air masses. The shallow depth of the cold air was indicated by the pronounced cooling from the surface up to the 950-mb. level. The cross section from Lakehurst, N. J., to Nashville, Tenn. (fig. 7), illustrates the spatial distribution of the cooling in the free air during the 24-hour period from 1500 GMT, May 17 to 1500 GMT, May 18. Nashville was selected to represent the changes in the warm air mass. Inspection of the north-south cross section for 1500 GMT, May 18 (fig. 8), yields a clear idea of the profile of the cold air along the length of the air mass.

The cold Low at the 700-mb. level at 0300 GMT, May 19 (fig. 9), was orientated northeast to southwest, just

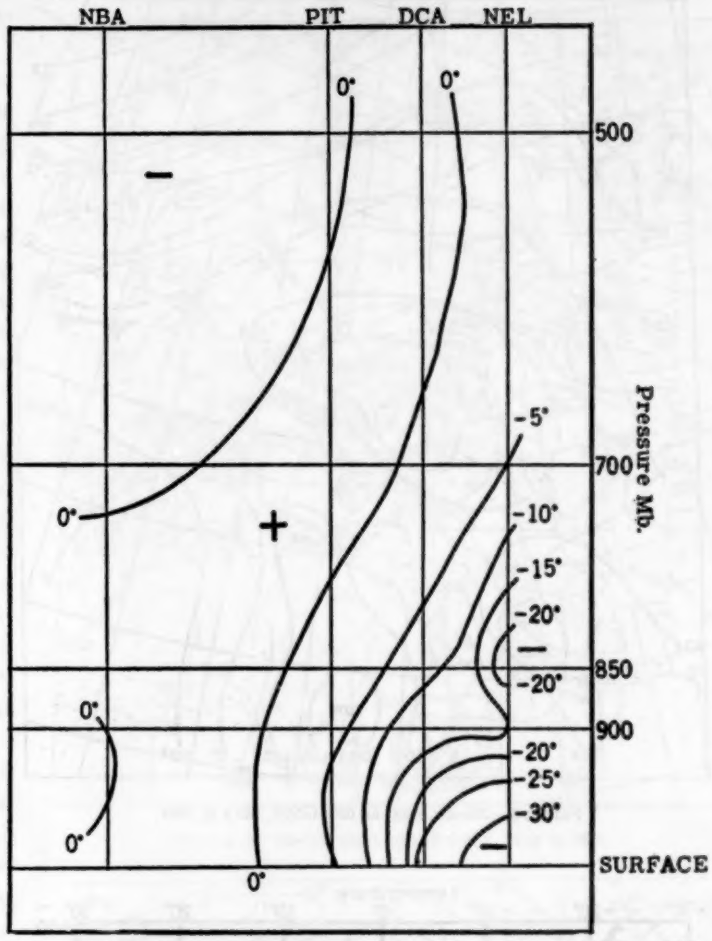


FIGURE 7.—Atmospheric cross-section showing 24-hour temperature change from 1500 GMT, May 17, to 1500 GMT, May 18, 1951. Isotherms (solid lines) are drawn for intervals of 5° F. Stations from left to right are: Nashville, Tenn. (NBA), Pittsburgh, Pa. (PIT), Washington, D. C. (DCA), and Lakehurst, N. J. (NEL).

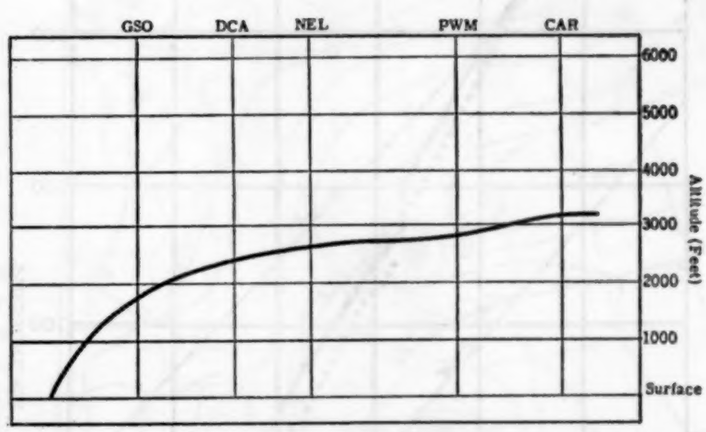


FIGURE 8.—Atmospheric cross-section showing North-South profile of cold air mass at 1500 GMT, May 18, 1951. Stations from left to right are: Greensboro, N. C. (GSO), Washington, D. C. (DCA), Lakehurst, N. J. (NEL), Portland, Maine (PWM), and Caribou, Maine (CAR).

off the Atlantic Coast from North Carolina to Florida. Inland the ridge split over the Ohio Valley forming one center over New York State and a second center over

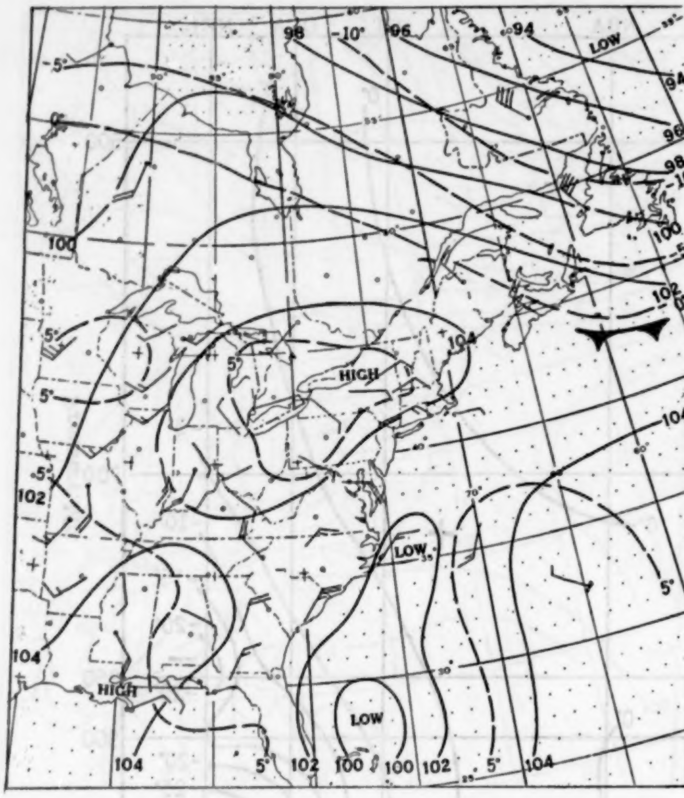


FIGURE 9.—700-mb. chart for 0300 GMT, May 19, 1951.

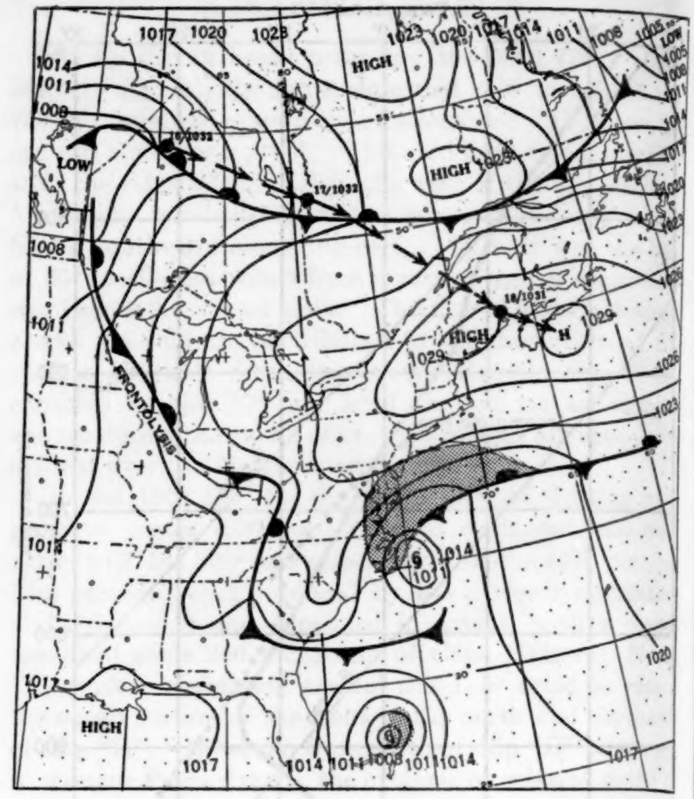


FIGURE. 10—Surface weather chart for 0630 GMT, May 19, 1951.

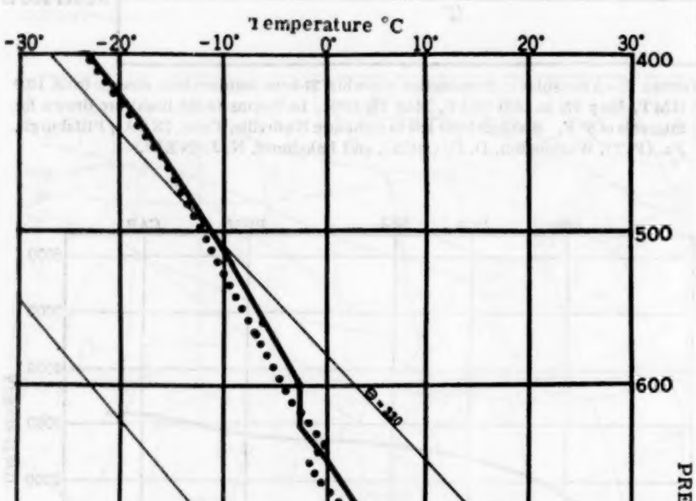


FIGURE 11.—Radiosonde observations (on a pseudo-adiabatic diagram) at Washington, D. C., for 0300 GMT, May 18, 1951 (dotted line), and 0300 GMT, May 19, 1951 (solid line).

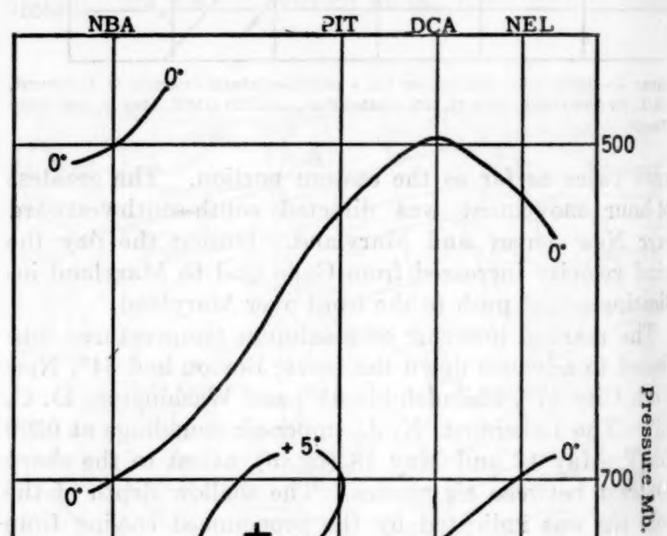


FIGURE 12.—Atmospheric cross-section showing 24-hour temperature change (° F.) from 1500 GMT, May 18, to 1500 GMT, May 19, 1951. (Stations are the same as those in fig. 7).

Mississippi. This rearrangement of flow pattern resulted in winds shifting to east from Washington, D. C., to Boston, Mass. In addition, the trough off the New England Coast rapidly disappeared as the High over New York State, and the northwestwardly advancing ridge from the oceanic High began to merge. As a consequence, east to southeast winds covered the area from Virginia to Massachusetts, and westward as far as Lakes Erie and Ontario. North of the newly forming ridge the winds were once more from a westerly direction.

On the surface, May 19 (fig. 10), the ocean portion of the front showed little movement from its position on the 18th, especially in the region 180 miles north of ship "H". The western boundary of the cold air ran from southwestern Pennsylvania, along the western slope of the Appalachian Mountains to northeastern Georgia.

During the day, temperatures remained below 70° from Maine to North Carolina. The soundings for 0300 GMT, May 18 and May 19 (fig. 11), show the depth and 24-hour cooling in the lower levels over Washington, D. C. The cross section (fig. 12), shows cooling during the 24 hours from 1500 GMT, May 18 to 1500 GMT, May 19. The greatest cooling took place at levels just above the surface.

With northeast surface winds both ahead of and behind the front, the cold air moved southward across Georgia. This flow, coupled with the southwest flow along the north side of the stalled Atlantic segment of the front, apparently contributed to the retardation of the movement of the ridge along the 45th parallel by virtue of the southwest air movement along the coast being greater than the southeast drift induced by the upper flow over the Nova Scotia area.

FINAL SITUATION

At the 700-mb. level on May 19, 1500 GMT (fig. 13), southeast winds had set in from North Carolina to Maine. At this level, as well as the 500-mb. level, the upper ridge gradually receded toward the southeast during the next 48 to 72 hours, thereby permitting the reestablishment of the more normal westerly wind regime over the region from Virginia northward.

The surface chart for May 20 (fig. 14), reflected these upper air changes. The air mass had become warmer, the front had become less well defined over the Southern States and had been wiped out over the New England States. Over the ocean the front persisted in just about the same position. The western limit of the cool air over the seaboard was identified by temperature differences over South Carolina and northward along the Appalachian Mountains to Pennsylvania. Although the air mass had modified considerably, maximum temperatures were below 70° along a narrow coastal strip from New York City to Cape Hatteras. Over the New England States, south winds had set in and the northern ridge had merged with the surface reflection of the upper warm ridge from the southeast. This was the last step in the history of the cold air which had moved far to the south in response to a peristent upper-air flow from the northeast and which in its turn disappeared when the upper-air pattern once more returned to normal.

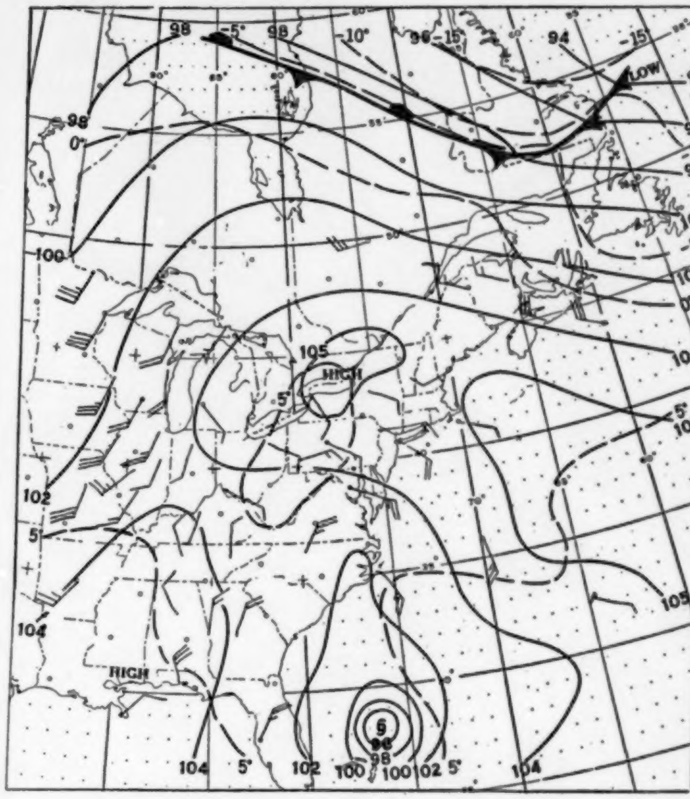


FIGURE 13.—700-mb. chart for 1500 GMT, May 19, 1951.

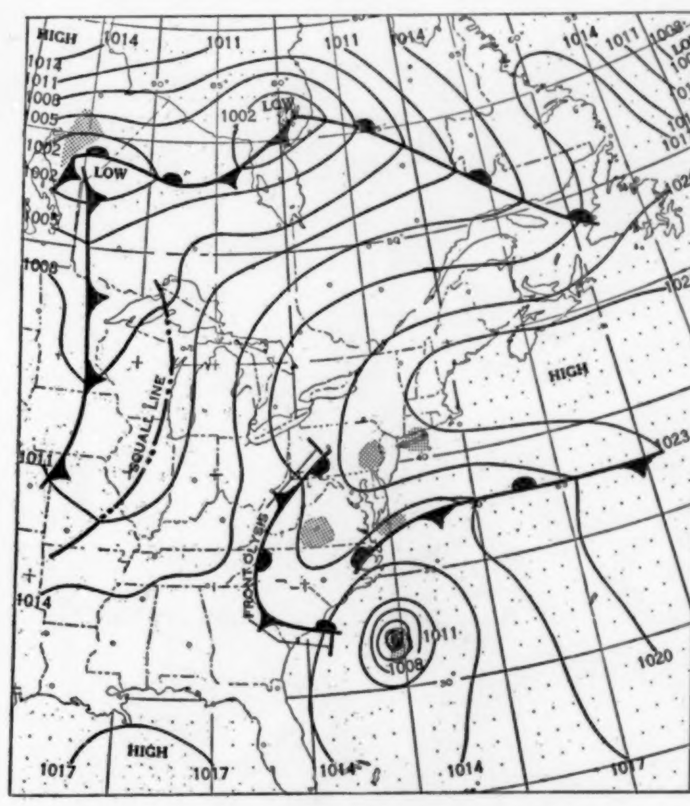
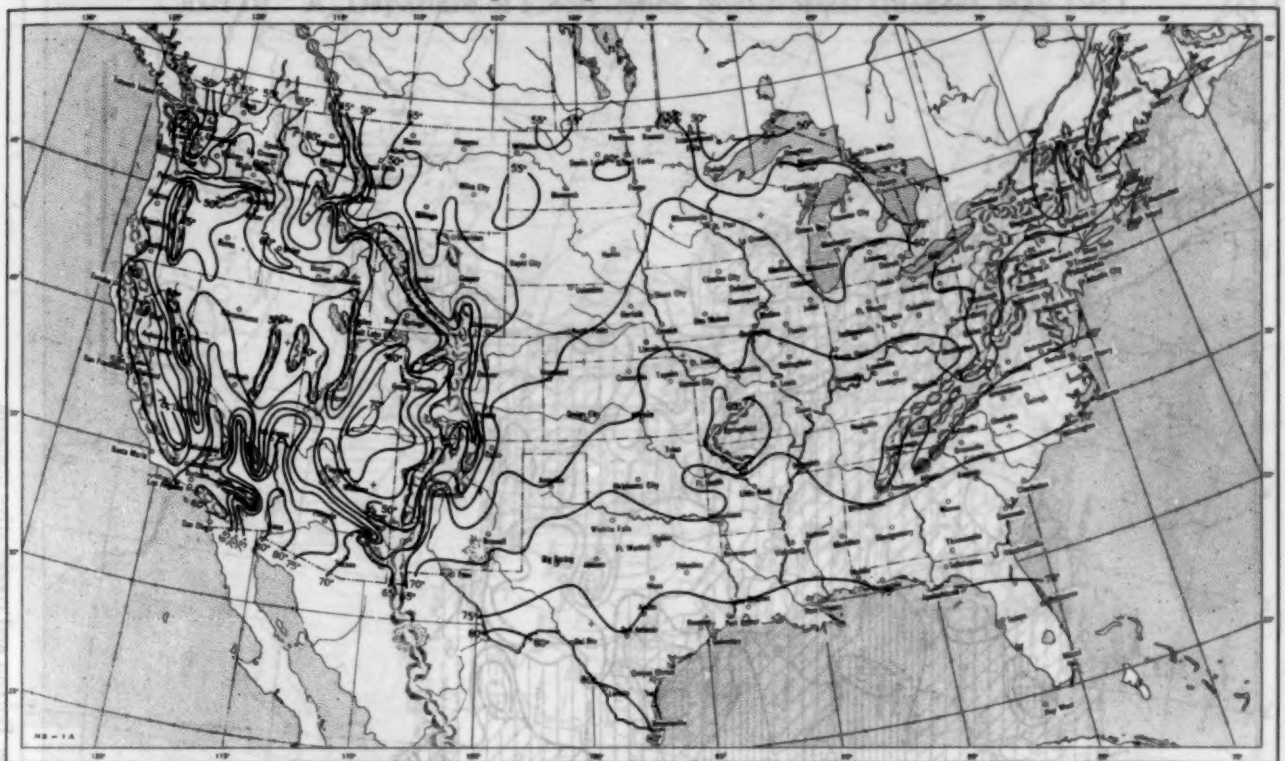
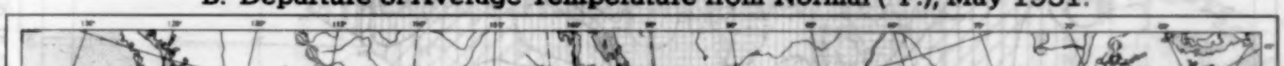


FIGURE 14.—Surface weather chart for 0630 GMT, May 20, 1951.

Chart I. A. Average Temperature (°F.) at Surface, May 1951.

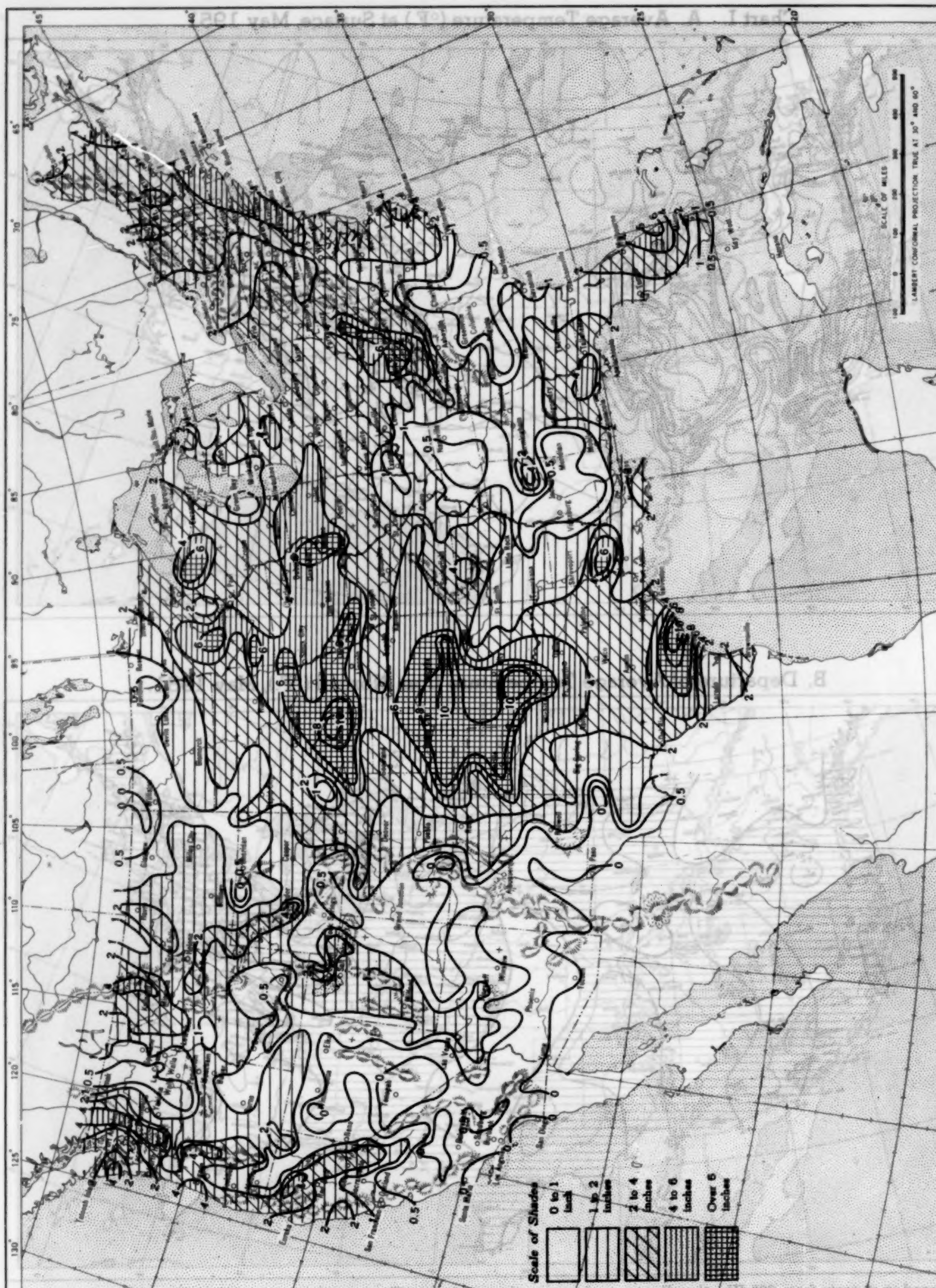


B. Departure of Average Temperature from Normal (°F.), May 1951.



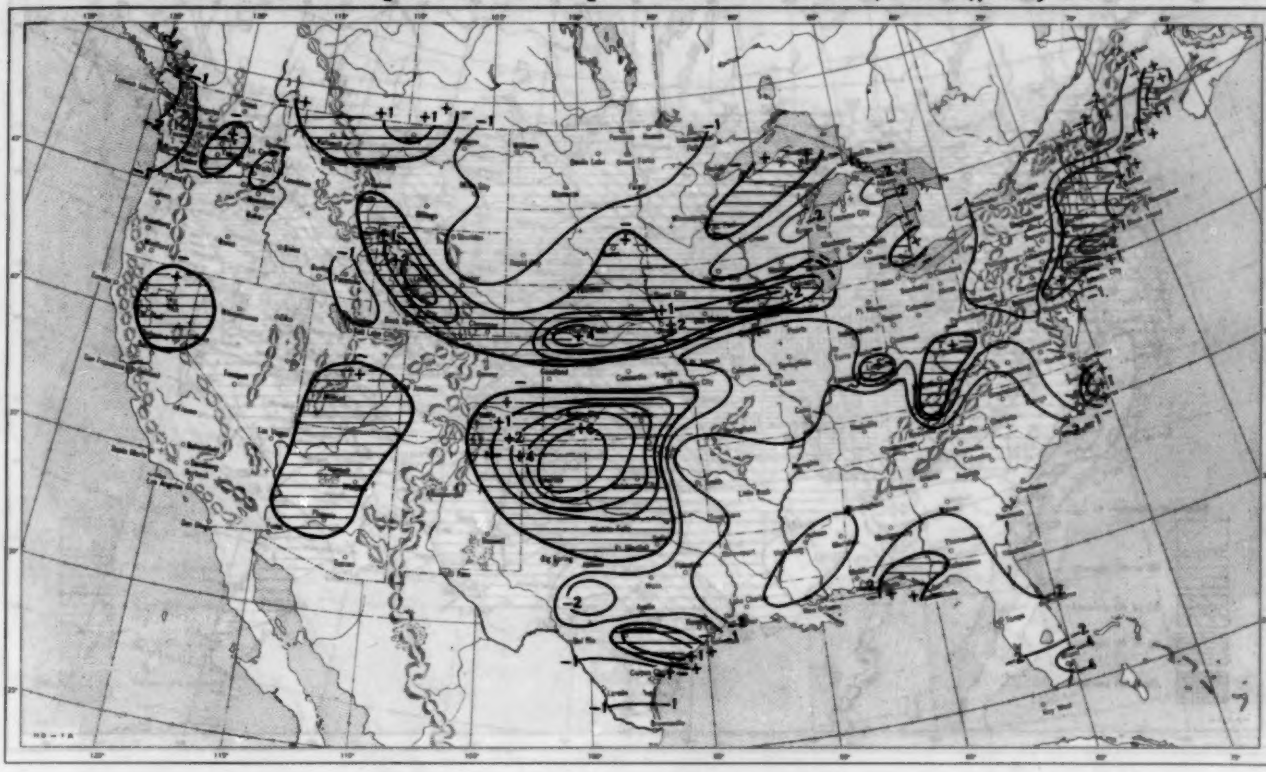
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), May 1951.

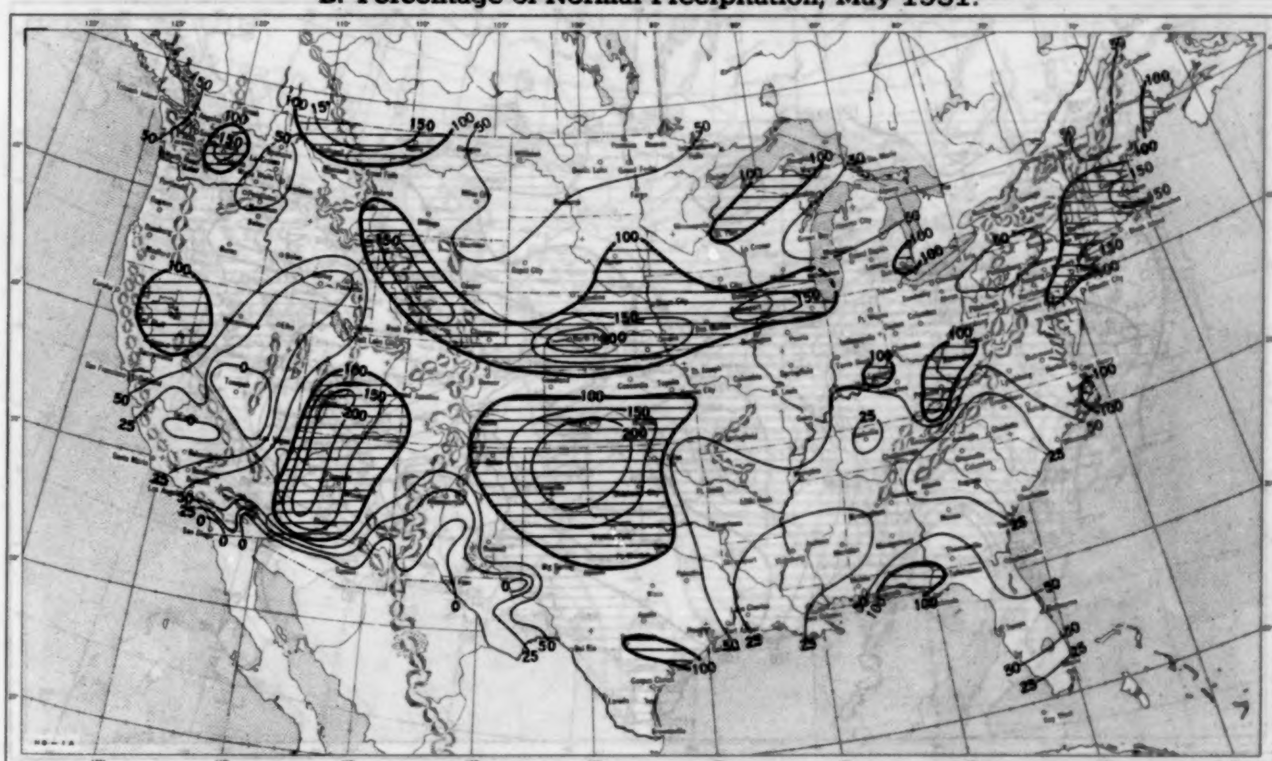


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), May 1951.

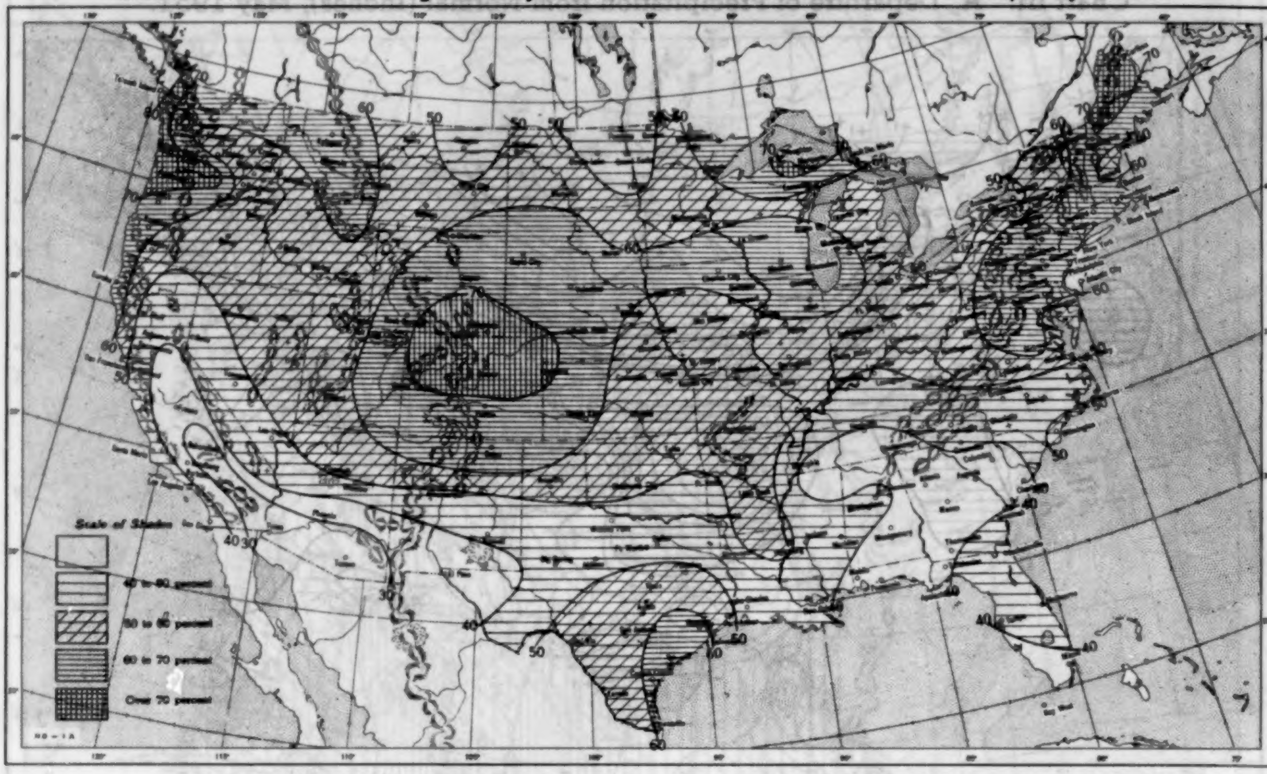


B. Percentage of Normal Precipitation, May 1951.

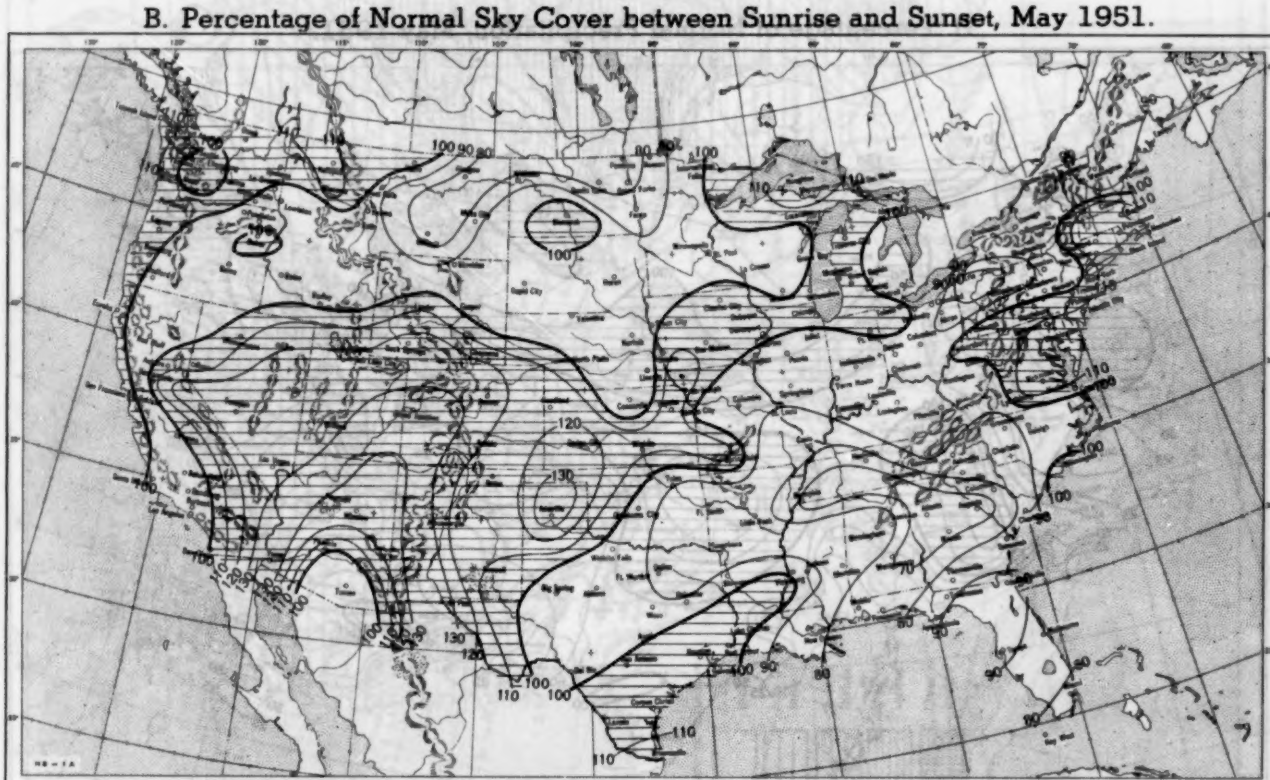


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, May 1951.

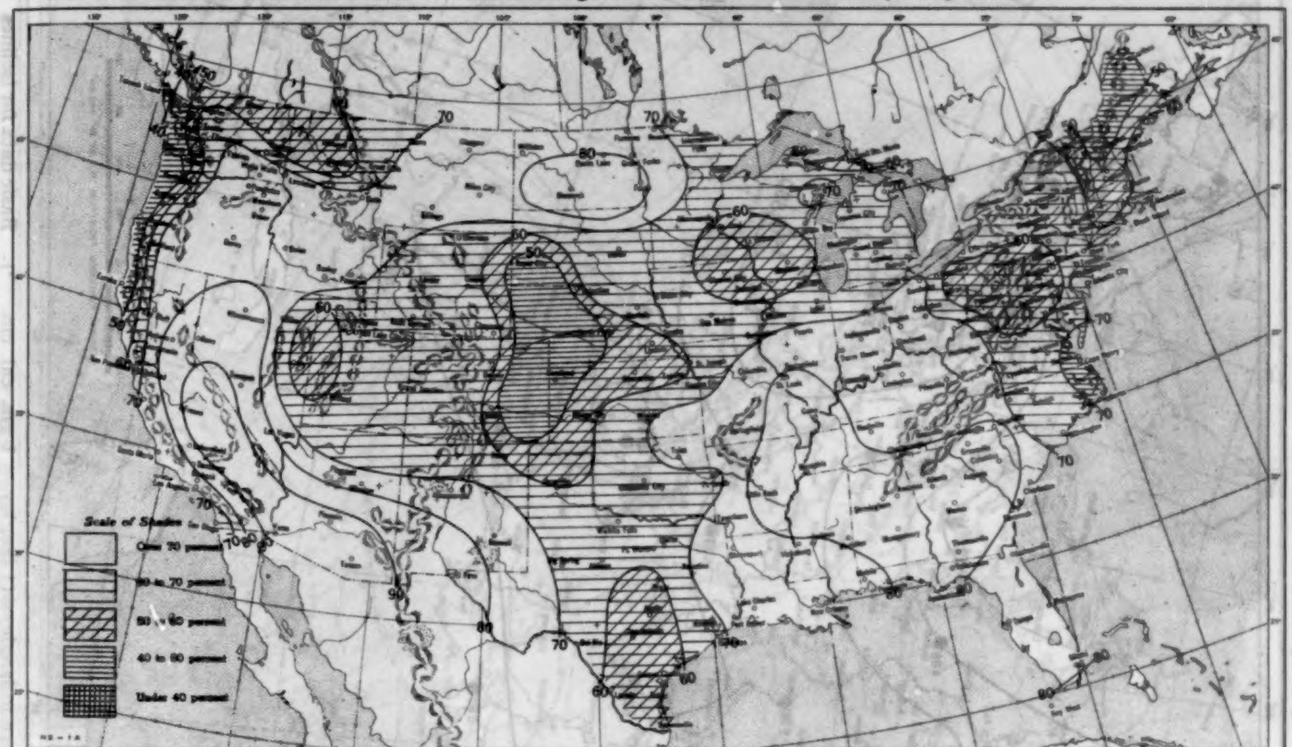


B. Percentage of Normal Sky Cover between Sunrise and Sunset, May 1951.



A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, May 1951.



B. Percentage of Normal Sunshine, May 1951.

A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, May 1951. Inset: Percentage of Normal Average Daily Solar Radiation, May 1951.

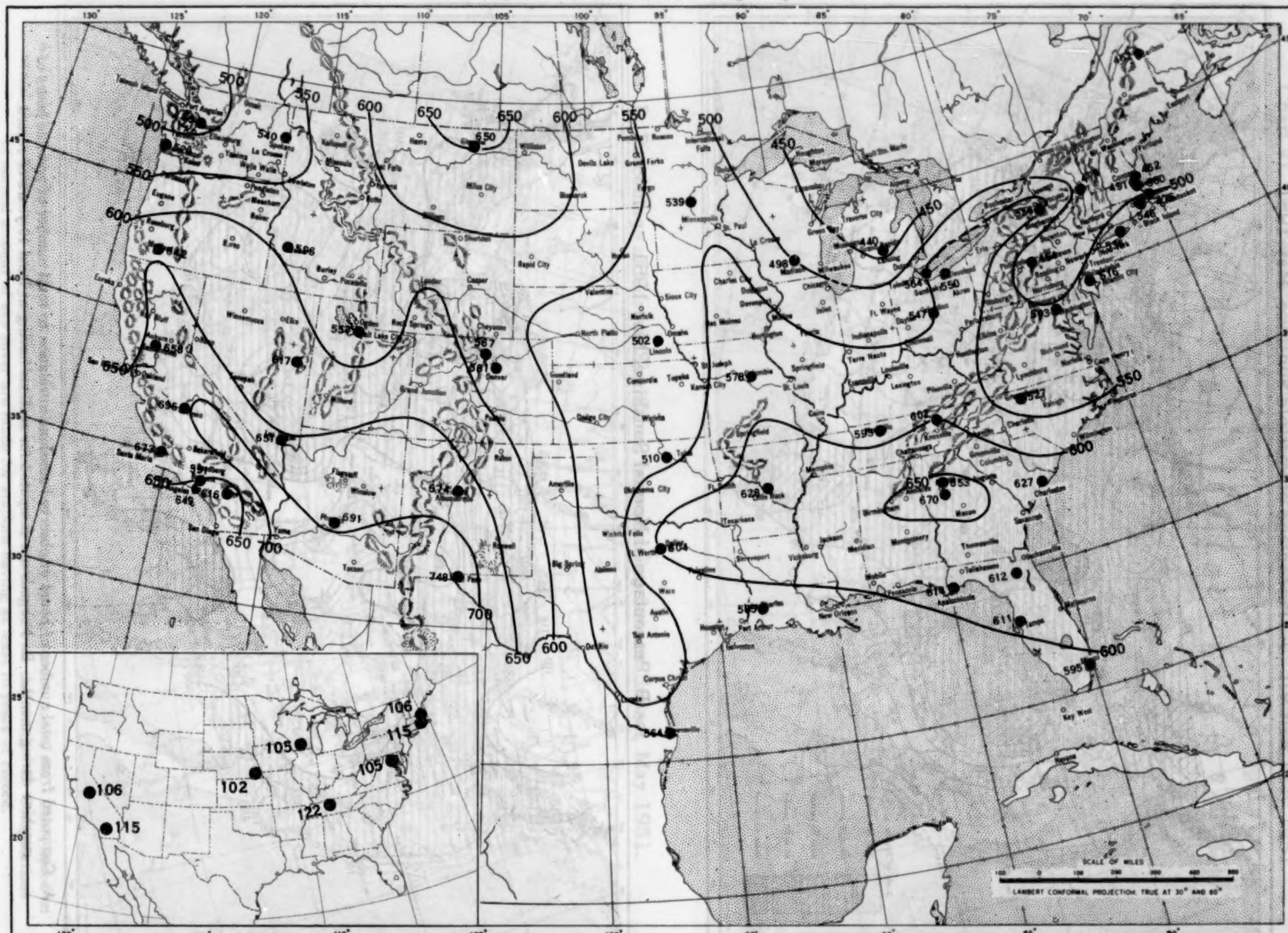
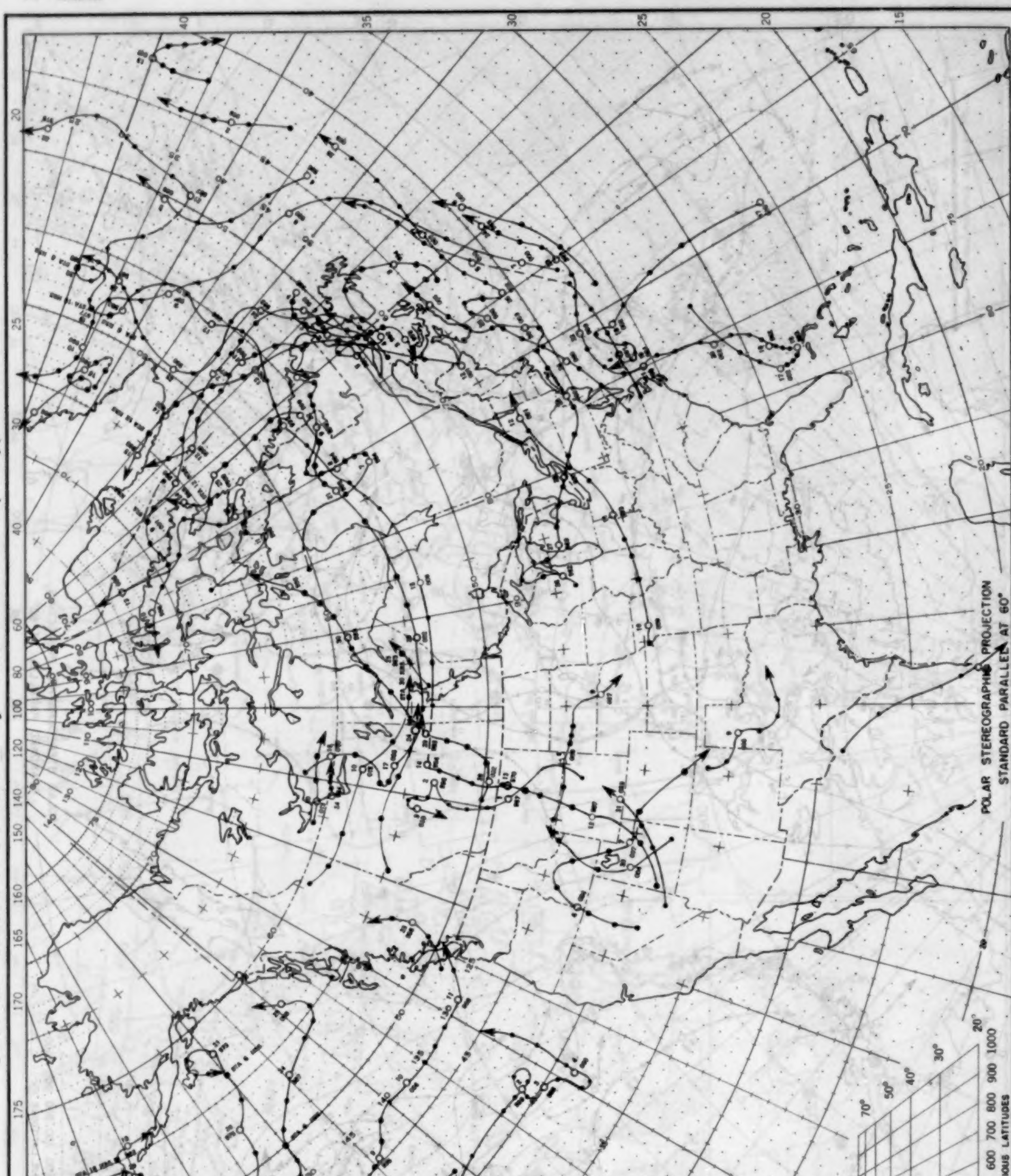


Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, May 1951

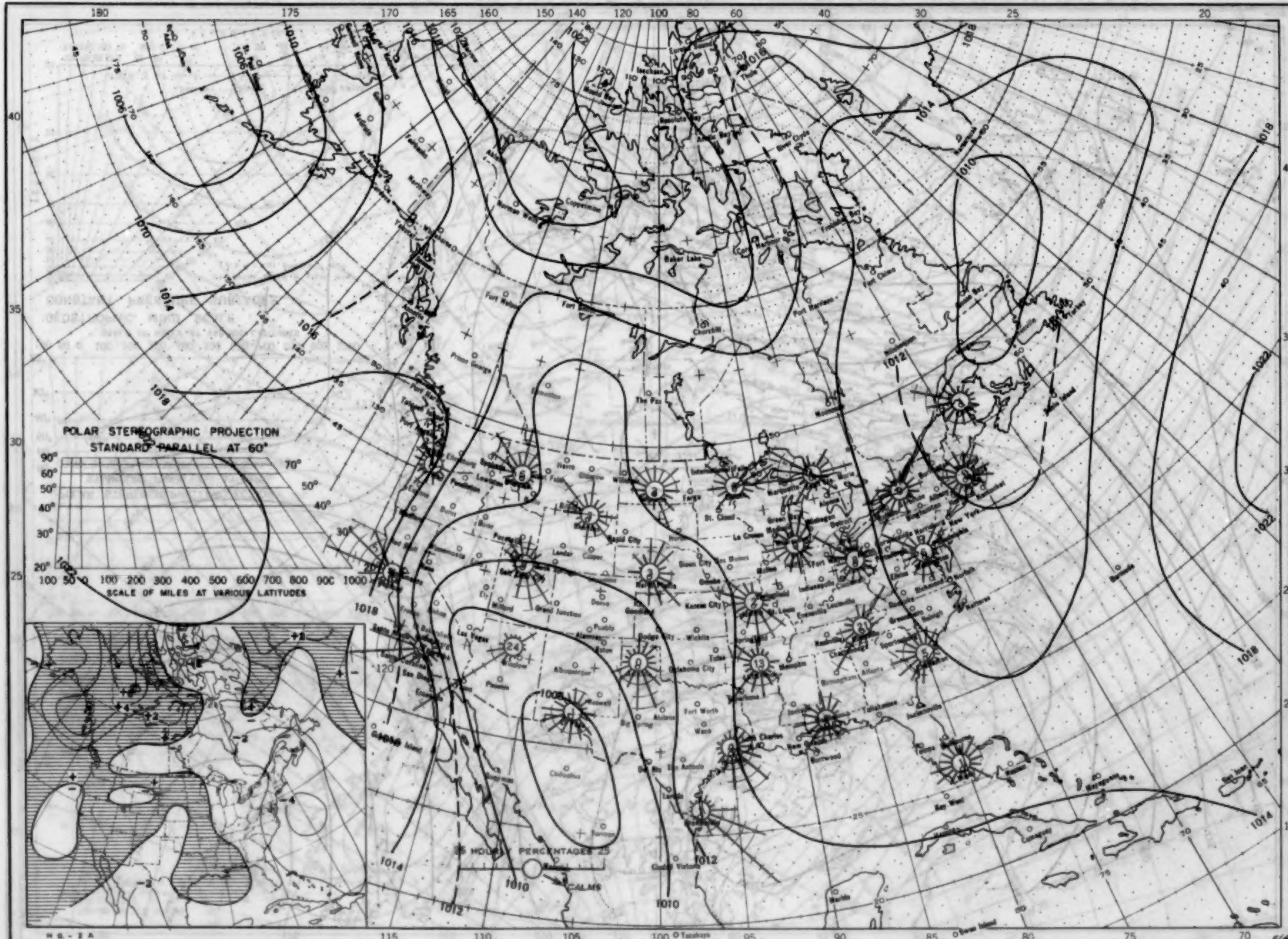
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, May, 1951.



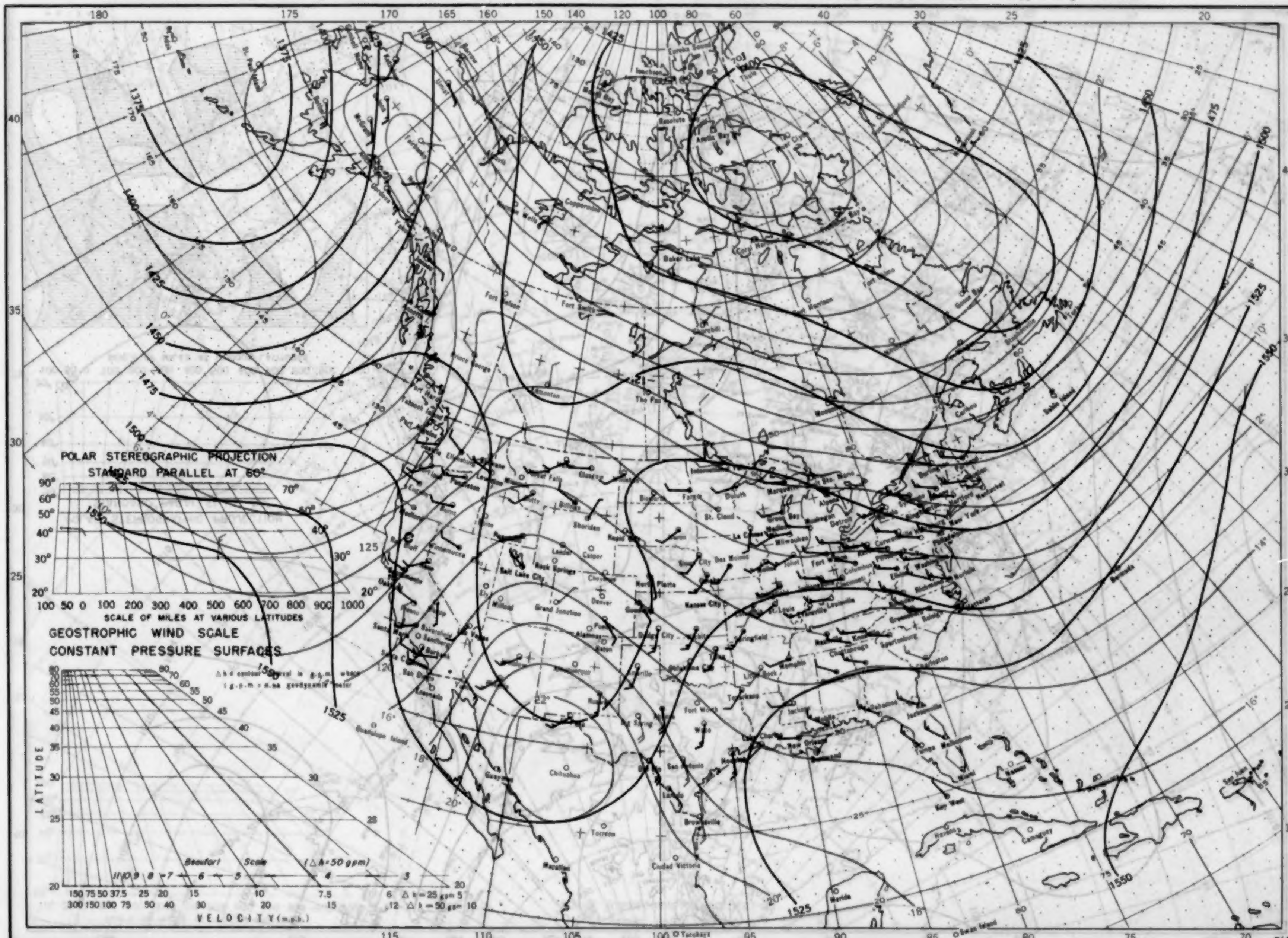
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, May 1951. Inset: Departure of Average Pressure (mb.) from Normal, May 1951.



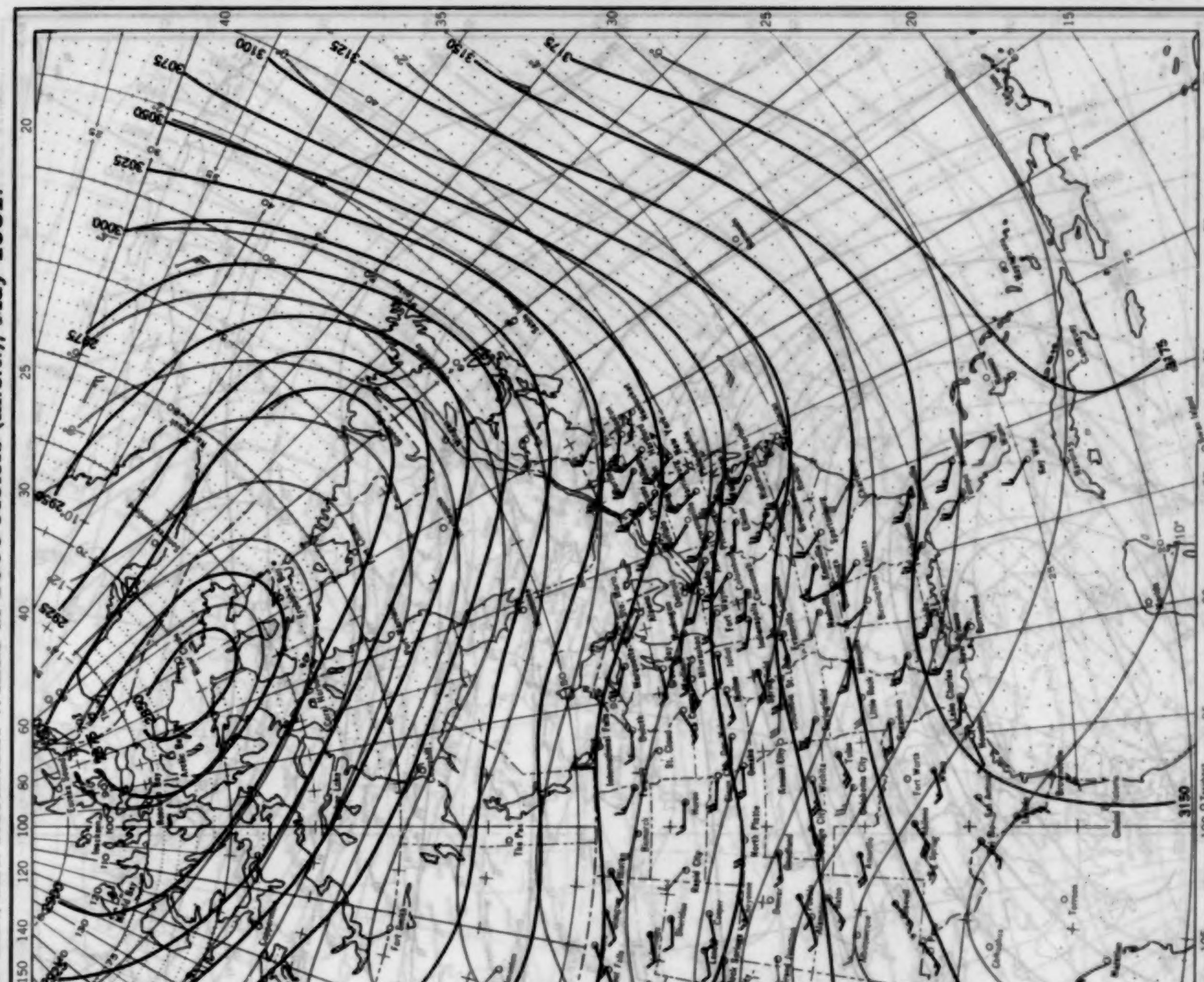
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), May 1951.



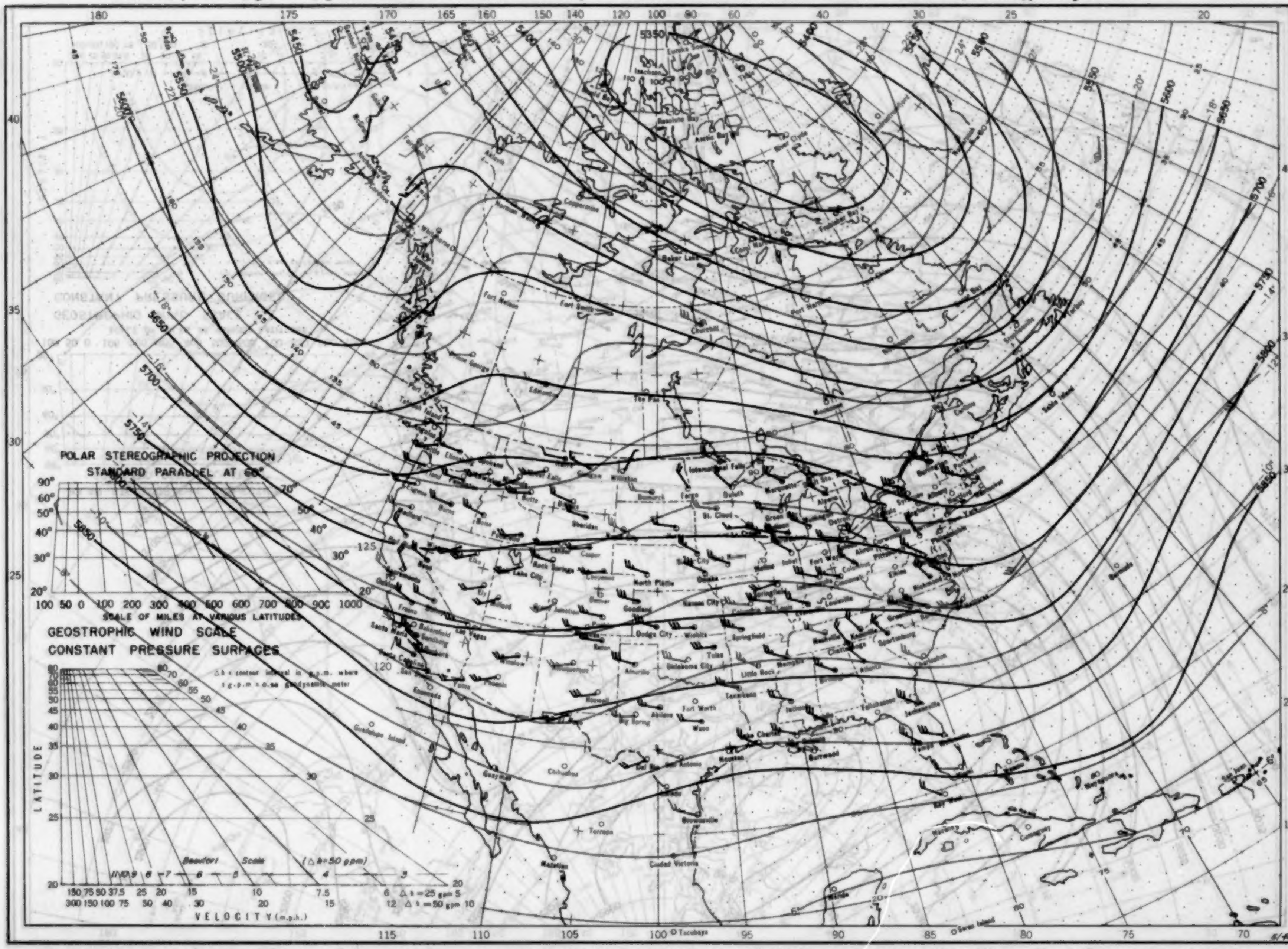
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), May 1951.



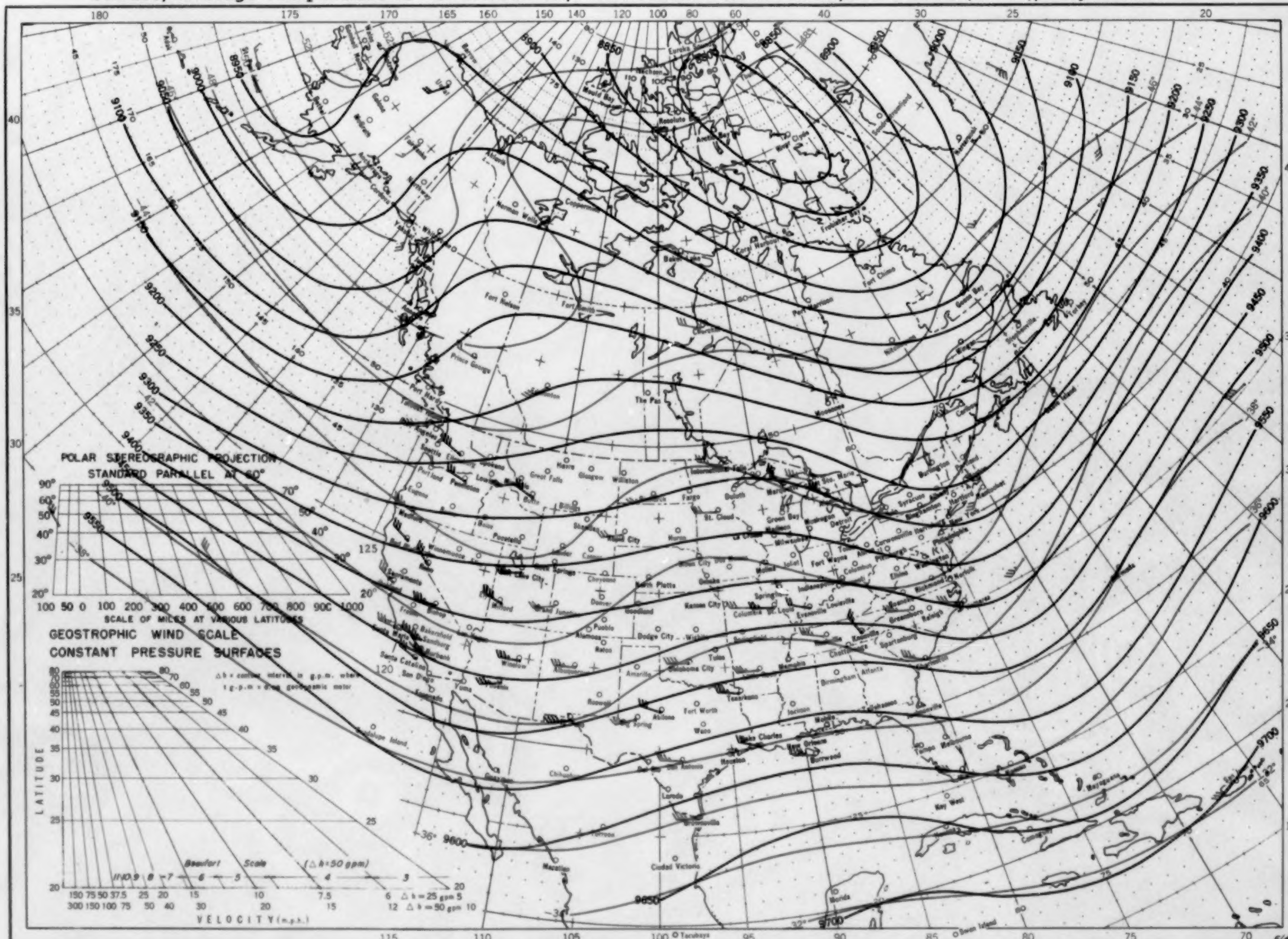
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), May 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), May 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.